Developments in
Earth Surface Processes 5

GEOMORPHOLOGICAL HAZARDS OF EUROPE

C. & C. EMBLETON

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GEOMORPHOLOGICAL HAZARDS OF EUROPE

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PREFACE AND ACKNOWLEDGEMENTS

At the 26th meeting of the International Geographical Union in Sydney, Australia, in August 1988, a Study Group on Rapid Geomorphological Hazards was set up under my chairmanship. It is worth noting that the original proposal was for the study of geomorphological hazards, broadly defined, and that the addition of the adjective "rapid" was not of my making. It will not be used in this book because any attempt at its definition will be quite arbitrary and pointless.

One of the tasks which the Study Group set itself was to compile a series of reports from different countries on geomorphological hazards. Originally, an attempt at world coverage was envisaged but the immensity and difficulty of this task was not fully appreciated until the first pilot reports were completed. It then became apparent that, for some countries, there is an overwhelming mass of information, statistics and maps on hazards, whereas for many more countries there is a notable lack. Because of the great variation in sizes of countries, it would also be impracticable to make text lengths proportional to area. Another problem was to find authors who would be willing to synthesise the information in a reasonable time - not easy in these days when academics are increasingly busy.

In various Newsletters of the Study Group, all members were invited to submit contributions on their own countries, and to suggest authors for countries not yet represented on the Study Group. Some of the most enthusiastic responders have still to deliver any report whatsoever! Within the first year, however, it was also becoming clear that several European countries would be producing full and detailed reports, and that no other continent was likely to be comprehensively covered, or nearly so, in a time span of 2-3 years. In the end, for reasons partly outside my control, that time scale has stretched considerably!

In this volume, more than 95 per cent of Europe in terms of area is covered. I will not list the countries that are missing, but merely say that vigorous attempts were made to obtain contributions from them, sadly with no success at the time that the volume was closed for printing purposes (31 October 1993). It has been very disappointing that some authors who agreed to contribute not only failed to do so but also failed to withdraw from the project, thus blocking the possibility of inviting others to write instead. I am tempted to name names! On the other side of the coin, I cannot adequately express my appreciation of the way in which some colleagues agreed to help in filling gaps at the very last minute. I want to single out four in particular: Irénée Heyse, Andrzej Rachocki, Nicholas Stephens and Helene Van Dorsser. They worked magnificently in a very short time to produce fine contributions to the book.

No attempt has been made to secure uniformity of coverage or style among the various countries. The way in which some chapters reflect the personality and interests of the author is, to my mind, a valuable feature. The term "geomorphological hazard" has been very broadly interpreted to mean any hazard to people or to their economic and social infrastructure caused by natural earth surface processes or, sometimes, by human-induced processes that, in most cases, involve change in relief. Some themes recur in every chapter, such as floods and landslides; others are more regionally concentrated, such as avalanches or permafrost hazards; yet others, such as lava flows in Sicily or bog bursts in Ireland, are peculiarly local phenomena.

The book also complements the text produced in 1984 on *The geomorphology of Europe*[1] by members of another IGU Commission (later Working Group), on Geomorphological Survey and Mapping. Professor Jaromir Demek, for many years Chairman of that Commission, gave invaluable advice on both that book and the present one. Several colleagues who wrote chapters or sections of chapters in *The Geomorphology of Europe* have also contributed to the present volume.

During the preparation of the text, there have been considerable political changes in Europe. The reunification of Germany meant an amalgamation of what were originally two separate chapters on East and West Germany. An opposite political process has divided former Czechoslovakia into Czechia and Slovakia, but as is explained in that Chapter, it was impracticable to separate the material into two, even if there were any point in doing so. A more complicated and tragic set of changes occurred in former Yugoslavia; the original text was prepared before these changes began and it would be quite impossible to fragment the chapter according to any newly emerging political units.

Some countries have wished to include their overseas territories - France, Portugal and Spain - and at the time that a worldwide survey, rather than a European one, was the aim, this inclusion was logical. The material contributed on these overseas territories has been retained in this volume rather than delay its publication to an indefinite future date.

Many of the line drawings have been modified or re-drawn in the Drawing Office of the Geography Department, King's College London. I wish to express my sincere thanks to Roma Beaumont and Gordon Reynell for their advice and professional skills in this work. Similarly, I would also like to thank Peter Howard, photographic technician in the Department, for his work in copying original photographs to reduced scales and in producing high-quality monochrome prints from some colour slides.

Clifford Embleton
October 1993

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[1] C.Embleton (ed.)(1984), *The geomorphology of Europe* (Macmillan, London), 465p.

When my husband died in July 1994 the outline of this book was set, the preparation of the material nearly complete and most of the text carefully edited. Clifford had spent four years on this work, of which the last two were interrupted by periods when he felt rather ill and by three long hospital stays. Even then, the book was top-most in his mind and any "good day" was devoted to work on it. I therefore naturally wanted do finish the task for him.

On the whole, what I have done is to tie up the loose-ends, prepare a new camera-ready copy and compile the indices. Unfortunately this has taken me over two years, struggling with two rather time consuming processes.

First, I had no clue about the whereabouts of the material, which in summer 1994 was literally dispersed over the whole of Europe. Clifford had partly prepared the book in Vienna and partly in London, using photo laboratories and drawing offices in both places and three different computers. On top of this, many parts of the text, figures and photos had been sent away to people for queries, completion of details or final corrections. Second, as Clifford's page-breaking was upset by incoming corrections and as word processing software is evolving fast, it was necessary to start the desk-top publishing process afresh.

For all the authors of this book, who naturally want to see their accounts completely up to date, I am sorry for the delay in publication. In sympathy with them I resisted the temptation of updating my own chapter on Austria. All the chapters are in their 1991-1993 state, depending on the time when they had been submitted. The fact that recent catastrophies are not listed can hardly impair the general value of this book, providing the first comprehensive survey of how the different European countries are hit by natural hazards and how the problems are dealt with.

I am grateful to good friends who helped me to finish this work for Clifford: Roma Beaumont, who dealt with all the faulty illustrations, Denys Brunsden and Robert Allison who checked the new pieces of text for me, and Dietlinde Mühlgassner, who assisted in various ways.

I am also grateful to Elsevier for their patience and for keeping open the possibility of eventual publication, even when little progress was apparent.

Christine Embleton-Hamann
October 1996

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CONTENTS

AUSTRIA

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1. Introduction

About 70 percent of Austria consists of mountainous terrain. It includes the greater part of the Eastern Alps, which in the west still support many glaciers. In the Pleistocene the ice cover was more or less complete, save for the highest peaks, and extended roughly as far east as the lower Enns valley. The ice was responsible not only for glacial erosion forms, often with steep relief, but also for the widespread deposition of unconsolidated sediments. The mountains are also a zone of active tectonic uplift, with a rate of about 2mm a year in the watershed area of the Eastern Alps. The high mountain climate promotes rapid rates of weathering and provides abundant precipitation to help in debris transport. Many factors therefore favour active geomorphological processes, whose direct effects are not only apparent in the mountains but can also reach out far into the Alpine foreland.

The intensity of the processes can sometimes reach catastrophic levels presenting a series of hazards to the population, the economy and its infrastructure. This chapter will deal in turn with the hazards of flooding, mass movements (including avalanches) and soil erosion; hazards associated with glaciers and permafrost, and finally those connected with seismic activity.

In terms of flooding there are fundamental differences between the lowland rivers and the rivers in mountainous areas, not only in respect of flood danger but also regarding the causes of floods, and counter-measures. In the upper reaches in mountain areas the main hazard is heavy sediment transport and deposition on valley floors. Many rivers here take the form of torrents (the so-called *Wildbäche*); in contrast, high-water stages in the middle and lower reaches appear as more familiar flood events. Because of these differences there are two separate authorities in the Austrian Ministry of Agriculture and Forestry (BMLF: see end of this section) dealing respectively with rivers and torrents.

Part of the damage associated with torrents is caused by debris flows. Other forms of mass movement that present serious hazards in Austria include landslides and avalanches.

These four major groups of catastrophic processes - river flooding, mountain torrents/debris flows, landslides and avalanches - are dealt with in most detail since they are potentially the most life-threatening. The remaining hazards - soil erosion, risks posed by advancing glaciers, by permafrost and by earth tremors are either rarely life-threatening or, in the case of glaciers, largely historical.

The Alps has long been known as an area subject to frequent natural catastrophes. In former times when the population was relatively sparse, catastrophic events had less economic impact: people lived with them and accepted them as a part of life, at the same time avoiding danger areas so far as possible (e.g. in the siting of settlements). In recent decades, however, there has been rapid expansion of settlement, mainly in response to the development of tourism which nowadays has overtaken agriculture as the prime source of income. Business capital has been heavily invested in these areas by outsiders with perhaps no experience of the natural conditions and possible hazards, and who all too frequently assume that hazards can be controlled by modern technology and that the government should pay for the necessary protective measures.

Whatever the justification for such a viewpoint, engineering works for hazard control are often expensive and rarely provide complete protection. There is an increasing realisation that two other approaches can be more successful and efficient, namely, the operation of strict planning controls (e.g. to prohibit building in danger zones) and, secondly, to work with nature, rather than against it, to combat the hazard. For example, forest conservation is vital in the fight against avalanches and torrent disasters, and flood retention basins can be an effective aid to flood mitigation.

Counter-measures and control of hazards in Austria are largely in the hands of the *Bundesministerium für Land- und Forstwirtschaft* (BMLF).

2. River flooding

2.1. Type and degree of flood danger

Floods on Austrian rivers occur mostly through prolonged heavy rainfall or through a combination of rainfall and snowmelt. Figure 1.1 shows that the heaviest rainfall is associated with the barrier effect of the mountains. The isolines of highest daily precipitation illustrate this clearly on the northern side of the Alps. A second area is located in the south of the country: here the north-south trending valleys of the Italian Alps direct Mediterranean air masses far into the mountains before they are forced to rise. A difference from torrent disasters should be noted at this point: in the case of torrents the most dangerous conditions are linked to the short and most intense rainfall events, which are not only caused by the barrier effect of the mountains but also by convective thunderstorms.

Because of the storage effect of snowcover many Austrian rivers show a seasonal regime that does not involve winter flood danger. Very occasionally damaging floods are related to ice jams. According to Prodinger (1975) such phenomena may occur in the upper reaches of Alpine rivers every 20 years. The area of the upper Mur and its tributaries, often called the cold pole of Austria, is particularly susceptible. In severe winters the ice must be broken by explosives. Also on the Danube the winters of 1828/29 and 1932 produced ice jams.

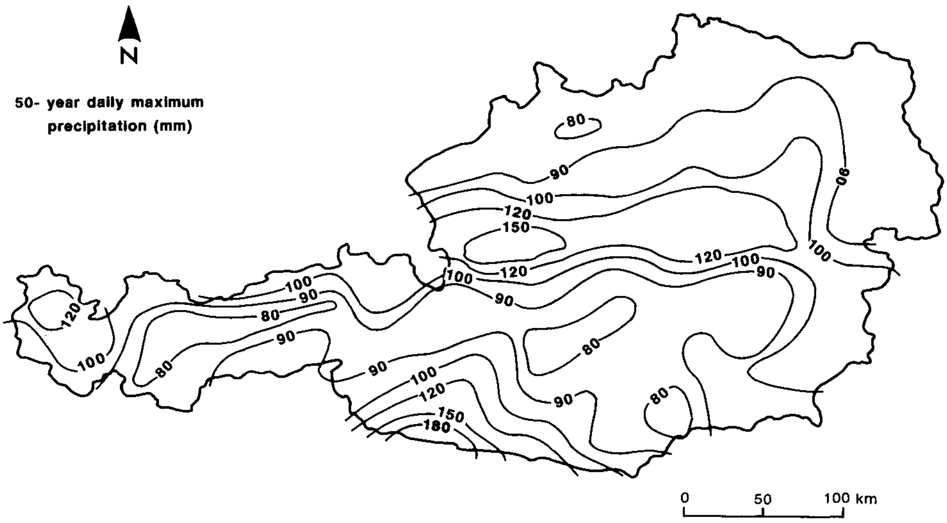


Fig.1.1. 50-year daily maximum precipitation (mm). *Source*: Figure 9D in Seebacher and Shanin (1985)

Almost the whole of Austria belongs to the Danube system excepting only a small part of the Rhine basin. The whole country north of the main Alpine ridge drains directly to the Danube across Austrian territory. Because of this unity two-thirds of the country experience approximately simultaneous flood danger from relief rainfall on the north side of the Alps. The most important catchments south of the main Alpine divide are those of the Drau and Mur which reach the Danube far outside the Austrian frontier. The most important Danube tributaries in the north are the Inn with its feeder the Salzach, the Traun and the Enns. All these main streams possess series of power stations.

River power stations without significant storage lead to an ambiguous situation with respect to flood risk. Their construction as a rule will improve local flood protection but at the same time the danger for places farther downstream is increased because of changes to the river gradient and the nature of the channel. These will increase the speed of the flood wave. If the operation of the power stations is properly interlinked, however, accurate flood warning can offset some of the disadvantages for the downstream area.

The water-level information service for shipping and flood warning was founded in Austria at the turn of the century. Forecasts are based on a network of automatic river gauging stations, which is being steadily increased in density. This information service is not only of national but of international importance. In terms of floods Austria is involved both in flood transmission to other countries downstream and in handling floods derived from upstream areas. For all cross-frontier main rivers there exist bilateral and multilateral agreements with neighbouring states. These deal with all questions of water management and impose a duty on the upstream countries to provide warnings of flood danger.

2.2. The flood disasters of the last 100 years

If one looks back on the flood events of the last 100 years, those of 1897 and 1899, 1954 and 1959, 1965 and 1966 stand out. The pairing of these events is deliberate: the second catastrophe in each case came hard on the heels of the first giving insufficient time for damage repair.

The July 1897 flood and the September 1899 flood affected the whole drainage area of the Danube north of the main Alpine divide and of course the Danube itself. The same was true for the flood disasters of 1954 and 1959. In 1954 the flood reached its peak in July and the flood waters in the Danube lowlands were up to 7 km broad; numerous settlements were submerged. In 1959 the acute flood danger lasted from mid-April to mid-August. During this time there were altogether five flood waves, which were progressively worse, partly due to increasing saturation of the soil.

The most catastrophic flood of the last 100 years was in 1965. On the one hand the rainfall was exceptionally pro-longed; on the other hand the convergence of weather systems between March and September led to record precipitation over the whole country. Even the normally relatively dry north-eastern areas suffered levels of flooding not previously known. The worst damage occurred in the Drau basin, which was severely affected by a deep depression from the Mediterranean in September. In the East Tyrol and western Carinthia almost all valleys were devastated and wholesale re-forming of river beds occurred. The next year (1966) saw two flood events, one in August and one in November, and once again the area worst affected was the Drau basin.

A detailed description of the flood disasters in Austria is given in BMLF (1973a).

2.3. Flood control in Austria

Sometime in the middle of the nineteenth century came the change-over from small-scale local attempts to control flooding, to large-scale flood protection works that involved hydraulic engineering and broader economic goals. For this, government finance had to be provided, the first legislation dating from 1830. Until the new law of 1884, however, money was only granted in practice for works of national importance and all other protection projects failed because of lack of money. After this date and up to the beginning of World War II a great deal was achieved; in contrast little or nothing was done during the war.

After 1945 river regulation and maintenance stagnated completely, but this time was marked by an uninterrupted series of small and large flood events, which finally culminated in the disasters of the 1950s and 1960s. There were then desperate attempts to catch up with the backlog of essential flood protection works.

The beginning of the 1970s marked a new era when engineers concentrated not only on damage repair but on longer-term river management and flood prevention. This was based on quite new principles; the construction of straightened and confined flood channels without water retention areas was to be abandoned, and flood danger was to be dealt with also at the regional planning level. In March 1972 a corresponding decree of the BMLF was issued with the title: Aspects of water management in the context of optimum environmental protection and regional planning (integrated measures for flood prevention) (BMLF, 1973b).

The new goals demanded an emphasis on comprehensive planning. It was necessary to make an attempt at land-use zoning and to redirect intensive land use away from areas bordering rivers to avoid the need for more and more flood protection works. Further, flood protection by means of water retention areas involves broad-scale planning: individual flood protection works can no longer be considered in isolation but must be integrated at the wider level of whole river systems. The planning is done in three stages:

1) To establish the basic data requirement (*Grundsatzkonzept*), i.e. a survey of each catchment to provide planning data

2) From that, to derive hazard zone maps and to plan protection measures for each catchment (*Generelles Projekt*)

3) Further, to derive final construction plans for each project.

Under (1), the following data are assembled and mapped (Schmidt and Raith, 1980): a) characteristic values of discharge, sediment transport, groundwater flow, geological situation etc.; b) areas liable to flooding (normally for Q^{30} and Q^{100}, in some cases for other events); c) existing and expected land uses in these flood-risk areas; d) how far it is worth protecting these existing and planned land uses. The following guidelines are used in this assessment: areas of high cultural and economic value to be given maximum protection; settlements and important industries up to Q^{100}, areas of intensive agriculture and forestry up to Q^{30}. e) possibilities of restrictions on future land use or re-assignment of existing land uses (re-settlement, re-location, change of use).

Under (2), hazard zone maps of flood protection for 30 Districts (total number of Districts in Austria = 2300) were completed up to January 1991. Such mapping has not been pushed forward with the same urgency as mapping for torrent and avalanche control (see below), partly because the flood zoning maps do not have the force of law for planning purposes, unlike that for torrent and avalanche protection.

The contents of the *General Project* involve decisions on the extent of development and the type of flood protection (river regulation, dykes, channel deepening and other changes, use of retention basins, possible changes in land use) in each river section. The extent of development is determined by the maximum discharge protection that the flood regulation works can afford.

Table 1.1 shows the present state of planning for flood protection in which the rivers are ranked according to the sizes of their drainage basins. The progress of planning and the carrying out of the measures in accordance with the new guidelines is easier in the case of rivers which come under government administration, for in these cases the whole cost of the work is borne by the government, whereas in other cases only fifty per cent of the work is subsidised.

Table 1.1. Present state of planning for flood prevention (January 1991). *Source*: Beiträge zur Hydrographie Österreichs, vols. 22, 24,28,33,36,41,49 and 51 and information from the BMLF.

Drainage basin size km^2	Number of rivers	Under government administration	Basic data	General Project
			complete/partly complete	
>3000	9	9=100%	9=100%	4=44%
300-2999	80	17=21%	36=45%	16=20%
30-299	700	2	*	*

* data not separable from those given in the second line of the Table.

Flood protection for Vienna has been one of the most costly undertakings. Formerly, the braided river Danube around Vienna was up to 5km broad and normally impassable for travellers; after 1870, however, this was totally changed by the first major river regulation works. An artificial channel was constructed, designed for a maximum discharge of 11 000 m^3/s, and about 12 million m^3 of material was removed. These dimensions were unfortunately not big enough: quite soon the engineers became aware that flood protection for Vienna must be designed to cope with a flood of 14 000 m^3/s. In 1969 the second major Danube regulation works were at last started. An entirely new channel with a length of 22km and a width of 160m ("New Danube") was constructed, separated from the old channel by the so-called "Danube Island", 200m broad. The construction of this by-pass not only served for flood relief, but also helped to improve the groundwater situation and to provide a new recreation and bathing area for the citizens of Vienna.

3. Mountain torrents and debris flows

3.1. Characteristics and types of mountain torrent

In the Austrian forest law of 1975 a mountain torrent (*Wildbach*, literally a wild stream) was defined as a permanent or ephemeral stream, liable to flash floods which pick up dangerously large loads from either the drainage basin or the stream bed; and which then transport and deposit the debris within or outside its bed, or in another stream (Fig.1.2).

Fig.1.2. View of the devastation caused by the debris flow of 7 September 1970 in the Rauris valley, Hohe Tauern. Several houses were damaged, as well as the road which had been partly repaired when the photograph was taken (*Copyright, Forstliche Bundesversuchsanstalt*)

In order that a stream should be treated by the BMLF as a "torrent", it must be officially recognized as such. Interpretation of the definition given above, however, varies according to the responsible official; therefore there is a range of phenomena that are classified officially as torrents. But in general, the following characteristics may be observed:

a) Strong gradient: in high Alpine regions up to 20 per cent, elsewhere in the Alpine region over 12 per cent (according to Aulitzky, 1984, Fig.4).

b) Relatively small catchment and correspondingly short stream length: according to Aulitzky (1986a) the mean length is between 4 and 6km.

c) High discharge peaks, since intense rainfall events cover the whole catchment and discharge rises quickly in the short steep courses. Between such events base flow is often negligible: exceptions to this are the torrents of glacier or karst regions.

d) Dangerously high loads of debris and other material (e.g. timber). In 1931, Stiny distinguished between "old" and "new" debris. Under old debris was included the loose material of glacial or fluvial Pleistocene and Sub-Recent formations. New debris comprised newly produced weathered material, particularly plentiful in areas of less resistant rocks such as schist, rocks strongly broken by tectonics and in the limestone Alps with their huge talus slopes. Because of continuous removal the new debris does not usually present such a danger as the old debris masses with their large stores. An exception to this is the situation where new debris builds up at the foot of large deep-seated mass movements (described in more detail in the section on mass movements, e.g. near Putschall in the Central Alps). As regards other material transported by the torrents, timber presents a particular danger, because of its ability to block the stream in narrow sections, followed by the catastrophic break-through of water and debris.

e) Most torrents end in debris cones or debris fans. The steeper debris cones are formed through transport of coarser debris; the gentler slopes of debris fans are associated with finer material. Exceptionally these features are lacking, where a torrent debouches into a river capable of removing the debris or where debris can be adequately deposited within the lower part of the torrent channel.

The greater the store of debris in the drainage basin, the greater the danger from the torrent. In extreme cases debris flows develop, which are characteristic of the most dangerous type of torrent. In a debris flow (*Mure*) the solid material is distributed throughout the cross-sectional area of the flow, which turns into a water-mud-gravel mixture, no longer obeying the laws of hydraulics. High speeds can be reached - for one such debris flow in the Tyrol the speed at the apex of the debris cone was about 100km/hour (Aulitzky, 1989); the total weight of debris transported can be immense, individual blocks more than 300m^3 have been known to be transported, and the flow can rise high up in the channel. All these characteristics can cause great destruction.

As well as this most dangerous type of torrent (Type 1), three other types are distinguished by Aulitzky according to relative debris content: (2) torrents with high debris content but obeying the laws of hydraulics, (3) torrents with some debris content and (4) torrents without significant debris.

3.2. Torrent distribution and torrent zones in Austria

As two-thirds of Austria is mountainous, torrent catchments cover a large area: in 1980 there were altogether 8933 torrents registered as such (Aulitzky, 1984).

Figure 1.3 shows the regional distribution of torrent hazards in Austria. The source for this is the map of torrent zones published by Kronfellner-Kraus in 1989, which has been gradually built up over the years. The zone boundaries were drawn up in 1989

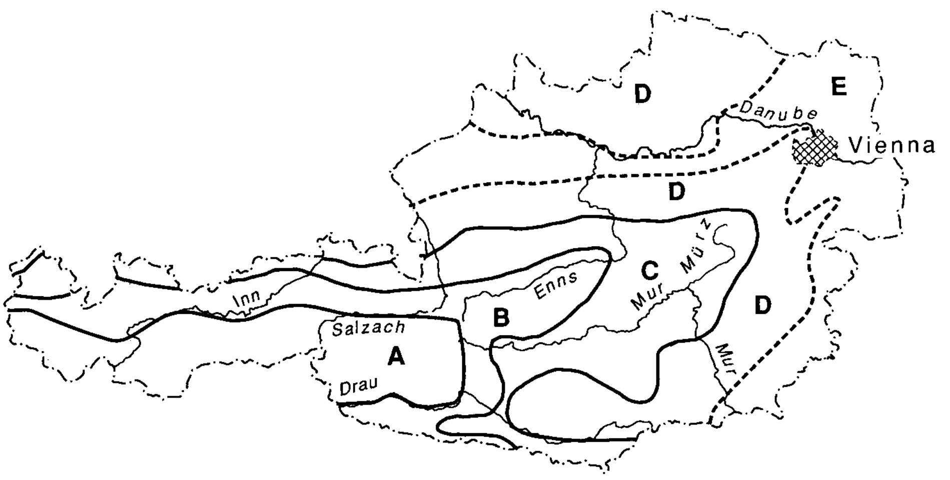


Fig.1.3. Torrent zones in Austria. *Source:* Kronfellner-Kraus (1989). For explanation, see Table 1.2.

Table 1.2. Torrent zones and types in Austria

Zone	Observed maximum debris loads (G. Kronfellner-Kraus, personal communication)	Percentage of torrent types (see text) based on H. Aulitzky (1986a)		
		Types 1+2	Type 3	Type 4
A	> 100 000m^3, exceptionally < 1 000 000m^3	81	19	-
B	100 000 - 200 000m^3	64	35	1
C	< 60 000m^3	33	55	12
D	< 20 000m^3	10	68	22
E	Loess gullies up to several thousand m^3; other torrents up to several hundred m^3	-	65	35

according to the debris loads involved in about 2000 torrent disasters from catchments up to 80km^2 in size. The map agrees well with the results of Aulitzky who approached the problem from another standpoint: his map of torrent distribution and hazard in Austria (Aulitzky, 1986a) is based on the different torrent types in individual districts. In Table 1.2, based on a comparison of the two maps, the proportions of different torrent types have been calculated for each zone.

Large and dangerous "old" debris stores are characteristic of zone A, which corresponds to the highest relief of the main Alpine watershed. This is the reason why types 1 and 2 dominate zone A (81 per cent). Old debris stores can also be present in zone B, but are usually smaller and not so common.

While zone A is clearly marked by the presence of old debris stores, the triggering factors for torrent disasters in zones B and C are more complex. They comprise mountain ridges mainly of schist and limestone where "new" weathered debris is actively forming. Moreover both zones lie in high precipitation areas (see Fig.1.1). In limestone and dolomite areas, the developing flood wave can be mitigated by underground drainage systems, but not in the case of schist. The immediate causes for torrent disasters in zones B and C can therefore vary regionally, but altogether, compared with zone A, there is less danger from individual torrents because of smaller debris stores, but at the same time there are greater numbers of torrents.

In the Pre-Alpine region and in areas beyond the Alps there is an abrupt decrease in the debris danger and torrent density (zones D and E). Zone E has no problems apart from those associated with loess gullies. The latter are often caused by unsuitable agricultural practices and are mostly quite recent.

3.3. Torrent damage

Since 1971 torrents and debris flows in Austria have claimed the lives of 46 people, destroyed or damaged 3674 buildings and devastated 4273ha of productive land. Overall during the last twenty years the annual total of damaging events has remained at about 125 per year. Despite the various counter-measures there seems to have been no significant reduction in this score (Jeglitsch, 1990; Kronfellner-Kraus, 1990).

Figure 1.4, taken from data in Jeglitsch (1976, 1990) shows the distribution of torrent disasters for the period 1971-76; the map shows the frequency of disasters in different regions, a picture which agrees well with the pattern of intense precipitation (Fig. 1.1). However, it must be stressed that the amount of damage relating to individual disasters varies greatly. The most dangerous and damaging debris flows make up 25 per cent of the total number of cases; this agrees well with Jeglitsch's figure calculated for a longer time span. Note that the debris flows are concentrated in the high mountain area of torrent zone A.

3.4. Torrent control and torrent research in Austria

Since 1884 the state has taken responsibility for torrent control, following the terrible torrent disasters south of the main Alpine divide in 1882. The responsible department of the BMLF is the same as that for avalanche control. Their work falls under four headings: a) engineering construction, b) afforestation of high areas and forest conservation measures, c) hazard zone mapping for regional planning and d) research.

In spite of all the efforts of the torrent and avalanche control service, the total number of disasters in recent times shows no decline, for which the basic causes are

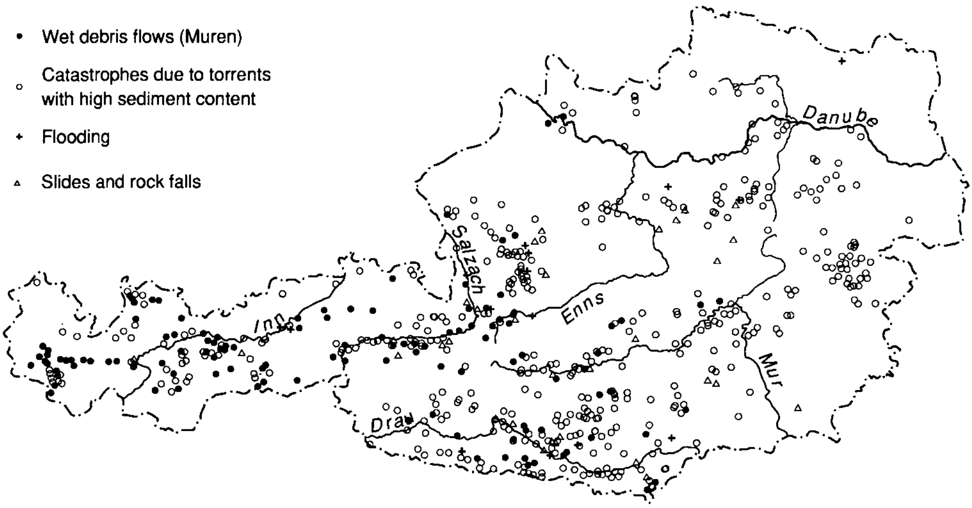


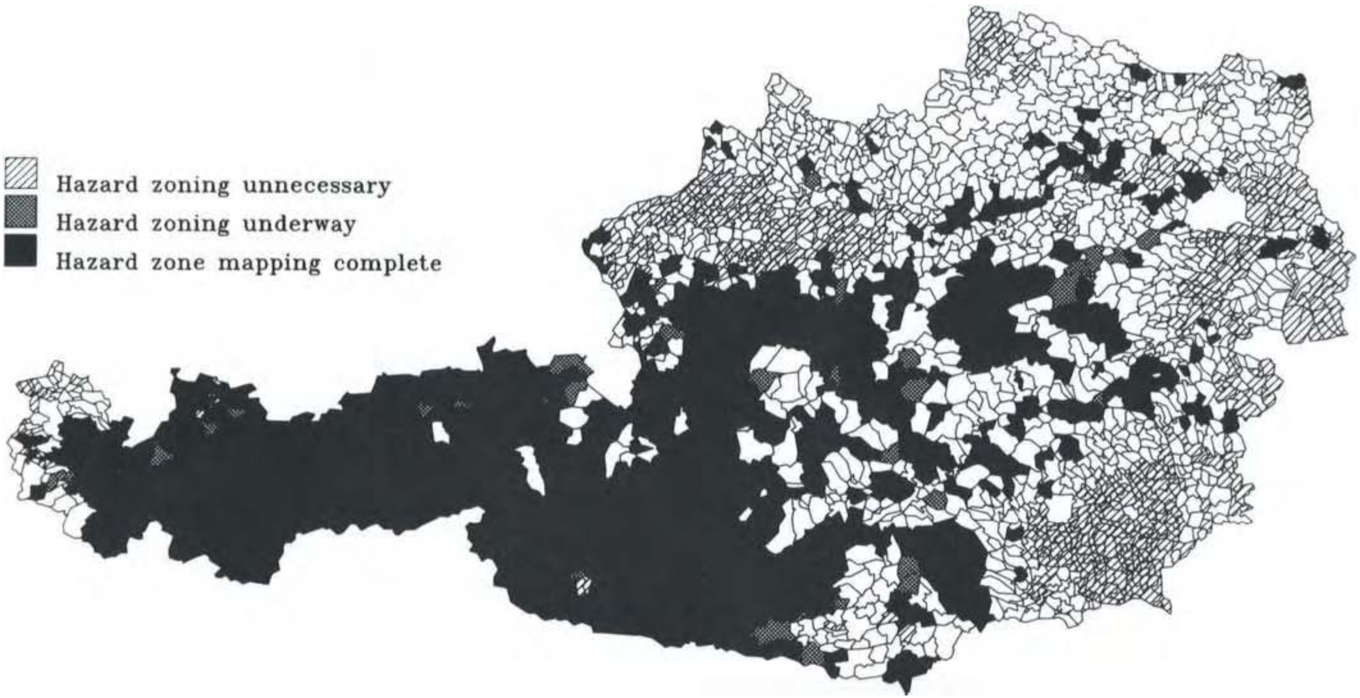
Fig.1.4. The distribution of torrent disasters during the period 1971-76

twofold: with the opening-up of the Alps for tourism came a huge expansion of the settlement areas which often occurred in potentially hazardous areas and which can only be protected at considerable cost. The second problem concerns the state of the forest.

Since interception of intense precipitation by the forest plays a vital role in the size of the corresponding flood wave its relevance to torrent control is clear. In avalanche control the forest has a decisive function in preventing dangerous levels of snow accumulation; therefore the problems of forest conservation and re-establishment will be dealt with in the section on avalanches.

The torrent and avalanche control service since 1975 has used hazard zone maps to prevent the unrestricted spread of settlement. The maps provide a legal basis for district planning and show the following features: a) torrent drainage basins and avalanche source areas; b) danger zones, the degree of danger being indicated on two levels as red and yellow zones, where the critical threshold for the red zone is a disaster return period of 150 years; c) areas where control measures are foreseen; d) areas where the possibility of other natural disasters such as mass movements is high. The map also marks natural or artificial features, e.g. dams, which have a protective effect and must be conserved. Hazard zone mapping in Austria has a high international standing and already covers a great part of the Alpine area (Fig.1.5).

The torrent and avalanche control service has its own research institutes for studying processes in torrent catchments and for avalanche research as well as an institute for forest study and mapping.


Hazard zoning unnecessary
Hazard zoning underway
Hazard zone mapping complete

Special mention should also be made of an international research body founded in Austria, following the disastrous flood events of 1965 and 1966 in Carinthia. A working party was set up which eventually developed into the *Society for the Study of Preventive Flood Control*. This holds an *Interpraevent Symposium* every four years which reports on the latest developments in disaster control and mitigation, especially in the fields of flooding, debris flows, landslides and avalanches.

4. Mass movements

In the last section, debris flows (*Muren*) were considered as an important special type of mass movement. This section will deal with all the other forms of mass movement involving rock and loose material, in which soil moisture and groundwater can play a vital role but in which water is not acting as a transporting agent. When such mass movements occur in a torrent drainage basin, they are recorded by the torrent control authority and are taken into account in their hazard zone plans and in their disaster statistics (see Fig.1.4). They are, however, documented more comprehensively and in greater detail by the Geological Survey, a department which comes under the Ministry of Science and Research. Up to now it has been estimated that the total number of both old and present-day landslides in Austria amounts to at least 60 000 (Schäffer, personal communication).

4.1. Regional distribution of landslides

Figure 1.6 shows the distribution of the most massive of all the mass movements, namely the *Bergstürze* (huge rockfalls and rock slides from steep mountain sides). They are by their nature confined to the Alps, and are more or less historic, rather than contemporary, phenomena. The Bergsturz at Sandling which occurred on 12 September 1920 (marked by S on Fig.1.6) and in which 6-8 million m^3 of rock were moved provides an exception. As Figure 1.6 shows, and as Abele (1974) notes, the total number of Bergstürze in the crystalline central Alps is less than in the northern and southern calcareous Alps. In general terms, this may be ascribed to the fact that the sedimentary areas are characterised by a broad-scale pattern of joints, fractures and bedding planes which allow very large slabs of rock to become detached and to slide, whereas in the metamorphic areas, the schists, gneisses and gneissose rocks tend to be less stable and to break away in smaller rock and debris falls. In terms of volume, the Bergstürze of Köfels, the Fern Pass and the Dobratsch (marked by their initial letters on Fig.1.6) are among the ten biggest occurrences in the whole of the Alps. The Bergsturz of Köfels (exact date uncertain, but ca. 8700 BP) stands out in particular, since all the remaining largest examples belong to the Limestone Alps. In the case of the Dobratsch, a huge area

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Fig.1.5 *(facing page)* The state of hazard-zone planing in Austria (as at 31 December 1990). Computer design by H.Fassmann

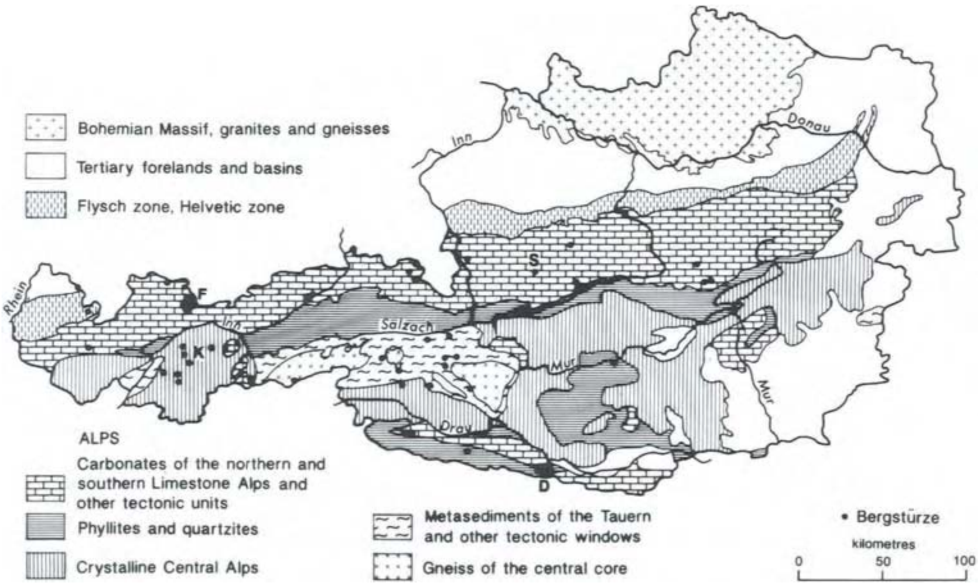


Fig.1.6. Geological sketch-map of Austria (after Tollmann and Vetters), and the distribution of Bergstürze (after Abele and Montandon)

consisting of 24km^2 of collapsed debris spreads out from its foot and represents the combined output of several Bergstürze. One of these, dating from 1348, is an example where an earthquake tremor is known to have provided the trigger mechanism (see section 9). Many of the other huge Bergstürze in the Alps seem to have occurred in the Late Glacial when the ice support of the oversteepened valley sides was removed.

Figure 1.6 also shows the main geological zones in Austria. Some formations are more susceptible to life-threatening or damaging mass movement than others, and in the following the relative importance of geology - or more precisely, lithology - as a factor will be examined. In making some lithological generalisations, it must not be overlooked that locally it is not the rock formation but tectonics that is decisive. Apart from the existence of many old disturbances and related weak zones, the Alps mark a very mobile plate boundary of the Earth's crust where present-day movements are readily detectable. The uplift of the Eastern Alps in the watershed zone is of the order of millimetres per year, while lateral displacements in the northern calcareous Alps can even reach centimetres per year. The result is a loosening of the rocks along the zones of faulting and disturbance. In a number of specifically investigated areas of the Austrian Alps the relationship between tectonics and major mass movements has been proved.

The factors of rock type and relief fundamentally determine the susceptibility to mass movement and allow the following broad regions to be distinguished:

The Bohemian Massif: In contrast to all other areas of Austria, this rates as a relatively problem-free zone. Built of resistant rock types (mainly granite and gneiss), and with a relief dominated by extensive plateaus, low height differences and gentle gradients, the majority of slopes are stable.

The Tertiary Foreland and Basins: The Tertiary sediments contain layers of sand, silt, clay and marl, which can be very susceptible to mass movement when the soil moisture content is high. Problems of slope failure occur especially during road construction and are frequent in the hilly areas such as eastern Styria. In December 1985 a 150-metre section of the newly opened Südautobahn (south motorway) collapsed by as much as 15m (Fig.1.7).

Fig.1.7. A section of the newly-built Süd-Autobahn which collapsed in December 1985, a few days after the road was opened (Copyright, Franz Pauritsch)

The Flysch and Helvetic zones: The sandstones and shales of this pre-alpine zone are very liable to failure and mass movements, especially sliding, are therefore frequent. They are extensive in places, endangering settlements and important traffic links or supply networks. It is especially expensive to repair and maintain the huge water mains that carry water from the Limestone Alps across the flysch zone to supply Vienna.

The Limestone Alps: The potential for danger arises essentially in the intercalated layers within the hard limestone or dolomite; these consist of unstable rocks, especially clay, shale, salt beds and gypsum. Within the calcareous zone, these comprise a quarter of the total outcrop. Although the number of mass movements is less than in the flysch zone, the scale of their activity and their dimensions are in general greater.

An area of about 30km^2 west and south of Sandling, already mentioned in connection with Bergstürze, is particularly liable to movement. The drainage basin of the Stambach provides an example from this area, in which the mass movements have been described in detail by Schäffer (1983). The limestone walls around the source region of the Stambach are unstable because of the underlying beds of clay and marl, the numerous joints in the limestone, and probably also because of neotectonic disturbances. In the years 1978 to 1981, three rockfalls each of which amounted to between 30 000 and 60 000m^3 broke away, falling on to older, probably late-glacial landslide debris, consisting of clay, marl and salt-bearing layers from the Limestone Alps. Loading of these by the rockfalls set them in motion, moving slowly downslope towards the valley, the movement continuing for one or two months on each occasion. In addition, a debris flow broke out of the loose material at the cliff foot. Substantial areas of forest were destroyed, along with a section of the Stambach valley road.

The phyllite and quartzite zone: The areas included in Figure 1.6 under this designation belong to different tectonic units, but their rock formations are bound together by a common characteristic - extreme susceptibility to landsliding. Because of its lower proportion of quartzite, the so-called greywacke zone is especially prone to problems. Lying between the central Alps and the northern Limestone Alps, it runs eastwards from the source regions of the Salzach. As well as numerous small landslides, there are also some large deep-seated mass movements, an example of which will be described on the next page.

The Central Alps: This zone is dominated by metamorphic rock types, though at the same time there is great diversity in detail, ranging from massive rock to strongly foliated and cleaved formations. Correspondingly, there is great variety in types of mass movement. The area of metasediments in the Tauern window is recognised as a particularly unstable one, since its position in the Alpine nappe structure has exposed it to exceptional tectonic stresses. These, together with the other important factors of steep slopes, high precipitation totals, and rapid infiltration through the broken rock, combine to promote extensive mass movement. Only the gneiss of the central core is relatively immune.

The huge mass movement near Putschall in Carinthia is located in the phyllite series on the southern border of the metasedimentary Tauern window with the crystalline rocks of the Central Alps. It involves the whole valley side, 1100m high, with gradients of

25-27°, over a distance of about a kilometre. At the top there is a scar 40m high where the break-away begins, while towards the foot the slope bulges out in convex fashion. Observations have shown that both creep and sliding are involved, and that the movements tend to be spasmodic and jerky, but averaging 50-60cm/year in the upper part and 20-30cm/year near the toe (Moser and Glumac, 1982). The mass movement threatens the village of Putschall below and some farms have had to be abandoned. Even worse than this direct hazard, however, is the possibility of an added risk of a torrent catastrophe. The moving valley side delivers completely broken debris to the river course at its foot; the debris is then washed out during floods. In the flood catastrophes of 1965 and 1966, part of Putschall had to be abandoned after being buried under debris up to 12m thick. Engineering measures to control such a torrent are tremendously expensive since the construction works have also to be able to resist the strong sideways pressure from the moving hillslope.

4.2. Recording of mass movements in Austria

Under the leadership of Schäffer, a project with the title *Documentation of geological-geotechnical risk factors* was started in 1979 by the Geological Survey. As well as the collation of many other data (e.g. relating to karstification, fluvial erosion, etc.), this work also embraced study of the distribution of all types of mass movement in Austria. Relevant, and often difficult to obtain, reports and scientific papers were collected, and the positions of individual landslides were identified on maps. Finally each map sheet was checked through field mapping and the inventory completed.

A product of this work has been a new map series entitled *Map of geological-geotechnical risk factors*, on a scale of 1:50 000, in which active slope movements as well as signs of impending slope failure (e.g. rupture zones, seepage zones, undercutting by erosion, hummocky ground) are plotted on a geological base map. In addition there is a table in which the units of the standard geological legend are reclassified according to rock stability, geotechnical properties (e.g. strength) and sensitivity to water penetration. Up to December 1991, 27 sheets of this map had been finished and can be consulted at the Geological Survey.

5. Avalanches

5.1. Causes of avalanches and avalanche types

Avalanches stem basically from lack of cohesion between the snow crystals or too little adhesion between the snow cover and the ground beneath, combined with stress changes in the snow cover.

The most important process leading to loss of cohesion is change in the crystal and snow structure during and after snow accumulation. These diagenetic changes vary according to the temperature and moisture content of the soil, snow and air as well as the effects of wind. They can lead to a diminution or an increase in grain size or the formation of crusts.

Diminution of grain size leads to denser packing of the snow and settling of the snow cover. During diagenesis, however, reduced cohesion of the snow crystals can produce an unstable situation. With increase of grain size there can be even greater danger: it leads to the so-called *Schwimmschnee* in which any cohesion between individual snow crystals is completely lacking. The term crust refers to a hardened snow surface, which develops either through freeze-thaw or wind pressure.

Diagenesis of new snow can therefore for a time lead to reduced cohesion in the uppermost layer of the snow cover. The cause of this is decrease of grain size and the triggering of the dangerous situation occurs through continuing heavy snowfall. On the other hand cohesionless snow represents a long-lasting danger if it leads to the formation of sliding surfaces under or within the snow cover. Such sliding surfaces are as a rule represented by layers of *Schwimmschnee* or old buried snow crusts.

Next to diagenetic changes, sudden rises in temperature or rainfall can reduce snow resistance. In this case the crystals become enveloped by a water film.

Strong stresses in the snow cover increase avalanche danger. They can arise through snow settling and through sliding and creep on steep slopes. Another cause is the increased loading from new snow or rainfall. Of course, given an unstable situation, the sudden addition of the weight of skiers can also result in an avalanche. Stresses also accumulate through temperature changes or locally in wind-driven snow.

To summarise, the most dangerous situations are created by heavy snowfalls, sudden temperature increases and strong winds, which cause snow drifting, formation of crusted surfaces and increased stresses. These facts are also brought out in avalanche statistics (Merwald,1985-89; Hauk *et al.*, 1986; Schaffhauser, 1988). For around 75 per cent of damaging avalanches in the period 1977/78 to 1986/87 the immediate causes could be determined. These were: new snow with strong wind transport (25 per cent), snow or sleet with rise in temperature (24 per cent), new snow (21 per cent), rise in temperature (16 per cent) and people (14 per cent). The remaining quarter resulted from a combination of causes, or the cause was not established.

There are various classifications of avalanche types, but only one emphasises the form of the break: powder-snow avalanches break away from a point, broadening downwards, whereas snow slab-avalanches break away along a line, below which the whole slab is set into motion.

Snow-slab avalanches are usually the cause of the greatest damage and unfortunately are also the more frequent. In the ten-year observation period winter 1977/78 to winter 1986/87 80 per cent of the avalanches were classified, from which 68 per cent were snow-slab avalanches and 32 per cent were of powder snow.

5.2. Distribution of avalanche danger in Austria

According to the Avalanche and Torrent Control Service there are over 5800 avalanche tracks in permanently settled areas. Most of them endanger only traffic routes. Most of the valleys originating near the main Alpine divide have only one exit and if this is threatened by avalanches the whole valley can be cut off for several days.

Around a thousand avalanches present a hazard to areas of settlement. Their distribution is shown in Fig.1.8. It must be stressed that this is only a preliminary map, since the only information available for its compilation consisted of a brochure designed for the general public (BMLF, 1989), which did not set out objective criteria for the recognition of avalanche tracks, nor was it related to a particular year.

Without doubt, however, Figure 1.8 shows clearly the areas of greatest danger. These comprise the high Alpine areas, where the steepness of the slopes favours the breaking-away of avalanches and the high altitude leads to considerable snow accumulation. Within the Alps, the map emphasises three regions where the avalanche risk is high. These are from west to east: the Arlberg region, the inner valleys of the western Tyrol, and somewhat less distinctly the inner valleys of Eastern Tyrol with 5 to 14 avalanche tracks per district. In these areas heavy snowfalls are particularly frequent owing to the blocking effect of the Alpine divide on weather fronts. Since the most frequent weather situations in winter involve air masses coming from the north-west, the Arlberg region and west Tyrol are at higher risk than the southern Alpine slopes of East Tyrol.

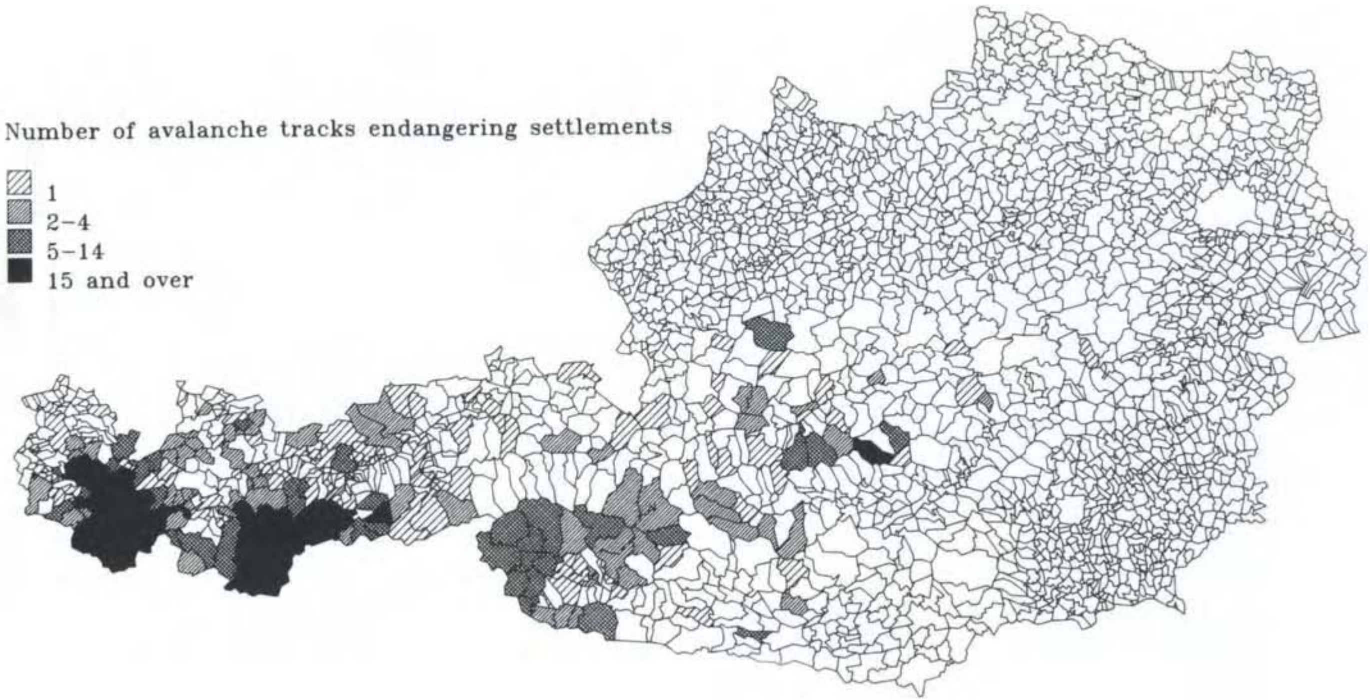
5.3. Avalanche catastrophes in Austria

The worst winter in the last half century was that of 1953/54, when 143 people lost their lives; damage was especially great in Vorarlberg, where 300 houses and other buildings were destroyed. There has been no subsequent event of such magnitude, but unfortunately from this it is not possible to conclude that protective measures and forecasts provided by the Avalanche Control Service have been particularly successful, since there has been no comparable weather situation subsequently. Altogether it is very difficult to assess the effect of avalanche protection because of the huge expansion of areas of settlement which now need protection (Aulitzky, 1986b): the problems of increasing costs and labour needs are similar to those of torrent control.

After 1954 the worst avalanche winters have been 1974/75, 1981/82 and 1983/84 (statistics only available up to 1986/87). Although in these winters there were avalanche deaths in settled areas, a category of visitor in much greater danger is that of skiers operating in uncontrolled areas: these are the off-piste skiers and a small but increasing number of ice climbers. Avalanche accidents causing death in the ten winters of the period 1977/78 to 1986/87 are distributed as follows: 75 per cent were involved in ski-touring in high Alpine areas (often despite warnings), 15 per cent inhabitants or visitors of settled areas, 7 per cent service personnel (rescue, avalanche warning and army officials), 2 per cent skiers on closed pistes and 1 per cent skiers on open pistes.

5.4. Avalanche control in Austria

5.4.1. Long-term avalanche control Alpine farmers in the seventeenth and eighteenth centuries had already established simple avalanche protection structures: some of them


Number of avalanche tracks endangering settlements
1
2–4
5–14
15 and over

are still effective today. In the last century the building of railways and military roads led to further measures to protect these new communication links.

After 1884 the government took on the task of avalanche control. The work of this branch of the BMLF has already been described in the section on Torrent Control in Austria (section 3.4). Note especially the advanced stage of hazard zone mapping, more or less covering the area which is prone to avalanche disasters (Fig.1.5). Since the Second World War the state has spent 2.3 billion Schillings (about 200 million US dollars) on protective measures for avalanche control including both constructional works and forestry.

The most difficult task in avalanche control today concerns the afforestation and preservation of protective forest in high areas where the area to be dealt with is continually expanding and new problems are constantly arising. Forest characterized by trees with varied heights, ages and a dense growth helps to lift the wind off the ground, to distribute the snow more equally, to prevent the formation of zones of tension in the snow cover, and to compact the snow around the tree trunks. This ideal forest structure has become seriously depleted over the centuries, requires much effort to be restored and is continually threatened by increasing man-made disturbance in recent times.

The areas which have to be afforested because of avalanche danger are increasing in size. On the one hand there is the rapid expansion of wintersports activity which until recently was extending ever farther into avalanche-prone areas above the tree line; on the other hand, land has been going out of farming for economic reasons. In many cases clearance areas (the alms) in the mountain forest dating from the Middle Ages no longer have the necessary intensive care lavished on them to prevent avalanche formation. Frequently today, tall grass has taken over, which provides a potential sliding surface for the snow. In these areas the traditional land use must either be restored or the areas re-afforested.

The necessary expansion of forest for avalanche protection, which involves caring for the young trees and encouraging natural reproduction, is frequently endangered today. Foresters complain of high deer populations, for these animals eat the young shoots and otherwise damage the young plants. The phenomenon of dying trees, of which acid rain is a major cause, now extends from the valleys up to the tree line and represents a long-term threat to the forest.

5.4.2. Temporary mitigation of the avalanche danger Measures here include warning, closure of pistes and roads, evacuation and artificial triggering of avalanches. Two bodies have responsibility here: the Avalanche Warning Service and the locally-based Avalanche Commissions.

The Avalanche Warning Service has existed since 1975 in all provinces in Austria with the exceptions of Lower Austria, Vienna and Burgenland. Relying on weather and

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Fig.1.8. *(facing page)* Avalanche tracks endangering settlements in Austria. *Source:* BMLF, 1989. Computer design by H.Fassmann

snow observations from representative meteorological stations, daily avalanche reports are distributed through the media of radio, press and telephone recordings.

The avalanche reports review the overall hazard situation and provide important data for the local avalanche commissions in assessing the level of danger. The commissions then decide which roads and pistes should be closed, which buildings evacuated, or whether artificial avalanche triggering should be employed to reduce the danger.

6. Soil erosion

The forms of soil erosion due to natural causes in the mountains and of gully erosion in general are monitored and controlled in Austria alongside those of torrents and debris flows. This section is concerned only with soil erosion caused by unsuitable land-use practices in agricultural areas. Because of the extent of forest and uncultivable land, the area under agriculture amounts to less than 50 per cent of the total area, or 3.55 million ha (as in 1987). This area has, however, in recent decades become increasingly affected by soil erosion as a result of the intensification of agriculture. Mechanization giving rise to larger and larger fields frequently ploughed downslope, replacement of soil protecting plants such as clover and lucerne by crops such as maize which afford little protection, and a change-over from grassland to arable on slopes, are among the main causes.

Monitoring of soil erosion in Austria is undertaken during soil survey. From as early as 1958 this has been carried out nationally; the mapping scale is 1:50 000. Mapping consists of the identification and outlining of groups of units with identical characteristics which are set out in an explanatory booklet. Also included are notes on erosion susceptibility and the degree of hazard. On request and subject to payment the soil survey will select information and produce a special map of soil erosion danger. It must be borne in mind that, although such objective criteria as slope angle, slope length, soil type and land use can provide guidelines in judging the degree of soil erosion danger, the cartographer's personal assessment will inevitably influence the end-product.

Statistical analysis of 99.5 per cent of the resulting maps was completed by June 1991, providing a rough assessment of the extent of soil erosion in Austria; the unpublished results of this work have been kindly made available by I.Povolny. In summary, 82 202ha are severely at risk from soil erosion by water and 511 129ha are in moderate danger, making a total of 593 331ha. This, however, is a minimum figure since soil erosion was not mapped in vineyards (55 950ha) nor for alpine meadows (829 913ha). Moreover soil erosion in maize-growing areas has increased markedly since mapping began. In regard to wind erosion, 20 947ha are strongly affected and 231 722ha moderately affected.

Klaghofer (in BMLF: *Beratungsschwerpunkt Bodengesundheit*) calculated the extent of soil erosion in Austria by another method. What he calls the "potential endangered area" is obtained by adding together the crop areas of maize, sugar beet and vines (1985: 431 000ha), and alpine meadows with slope angles exceeding 30 per cent, which he estimates at 300 000ha. The resulting total of about 750 000ha is rather high, since the most recent agricultural statistics (1987) show a decrease in maize, sugar beet and vines to 408 500 ha.

If Klaghofer's figures are reduced slightly and the soil survey estimates correspondingly raised, it appears that about 18-20 per cent of the cultivated area (including alpine meadows) is in danger from soil erosion. Wind erosion adds about another 7 per cent.

Regional differences in the intensity of soil erosion are difficult to estimate from these data. In the case of north-eastern Austria, it is well known, however, that the extensive areas of intensively cultivated loess are susceptible to both sheet and gully erosion. The lowlands of the east and north-east are also liable to wind erosion, especially the Vienna Basin and the Austrian part of the Little Hungarian Lowland; elsewhere in Austria wind erosion is not an important hazard.

The BMLF runs an advisory service for farmers, issuing directives and support material which is distributed through regional centres. In this way considerable advances have been made in the fight against soil erosion, especially in Styria and Lower Austria. Individual farmers are encouraged to undertake appropriate adjustments to farming practices, such as the planting of strips of wheat within fields of maize or sugar beet, crop rotations and straw mulching. In vineyards the spaces between the vines are kept under grass. In some cases these measures were not sufficient; for example in the vine-growing areas on the loess east of Krems, terracing has been necessary. In areas susceptible to wind erosion, wind speeds have been reduced by planting shelter belts of trees flanked by hedges (Povolny, 1983).

The Austrian Government has set up a special research institute to deal with questions of soil erosion and protective measures: this is the *Bundesanstalt für Kulturtechnik und Bodenwasserhaushalt* (Federal institute for agricultural technology and the soil water budget). Field experiments are being undertaken to ascertain what are the most effective protective measures; and theoretical investigations are being made to establish the parameters in the Universal Soil Loss Equation of Wischmeier and Smith which are most appropriate to conditions in Austria (e.g. Klaghofer and Summer, 1990).

7. Glacier hazards

There are two main types of potential glacier hazard: collapses and falls from glacier tongues (sometimes known as ice avalanches), often associated with periods of glacier advance, and hazards related to glacier meltwater, such as the bursting of ice-dammed lakes. There are no historical records of the first category, probably because glacier falls never appear to have threatened permanent settlements, but there are many records of the second category. There appear to have been two periods in recent historical time when meltwater catastrophes were particularly frequent and damaging - towards the end of the seventeenth century and during the nineteenth century (approximately 1830-90 with a maximum in the 1860s). Some of these catastrophes were owing to the bursting of supraglacial lakes or of marginal lakes dammed at the junction of glaciers. The two best-known cases are, however, related to the blocking of valleys by glacier tongues advancing into them; the resulting temporary lakes were the Rofener ice lake and the Gurgler ice lake in the Ötztaler Alps (Tyrol). The first of these, impounded during surges of the Vernagtferner, produced the larger catastrophes, including at least six damaging outbursts, causing almost total devastation in the Ötztal, a sudden rise in the water level of the Inn river at Innsbruck, and even on one occasion sending ice blocks into the Danube. In contrast, the Gurgler ice lake led to only two damaging events, neither of which attained the magnitude of the Rofener disasters. Normally, the Gurgler lake emptied only slowly. A detailed account of the events is given in Leys and Reinwarth (1975) and in Hoinkes (1969).

Since the beginning of this century, glaciers have on the whole been retreating, and consequently hazards on this scale have not recurred, nor are they likely to if retreat continues. On the other hand, any readvance such as typified the last century could have quite serious consequences, not only in terms of meltwater flooding but also in terms of the extensive development of, and facilities for, glacier skiing, since the whole infrastructure of this industry has been constructed within the 1850 moraines! (H. Slupetzky, personal communication). Theoretically, monitoring of glacier hazards falls within the purview of the Torrent and Avalanche Control service, but at present there are no such hazards to monitor.

8. Permafrost

It is now definitely known that permafrost exists in the high levels of the Austrian Alps, and it is more common than used to be thought. Prior to 1980, the possible existence of permafrost was not usually recognised, with the result that there were many technical engineering problems that proved costly to overcome. The number of scientific publications dealing with permafrost in Austria is still quite small, and none deals with the applied aspect. The following account was prepared with the kind assistance of Dr. G.K.Lieb (University of Graz) and Doz.H.Kerschner and Doz. G.Patzelt (University of Innsbruck).

Detailed mapping of permafrost distribution is restricted to a few small areas. Lieb has compiled a preliminary map of permafrost distribution (Fig.1.9) specifically for this report. In the area of the main Alpine ridge, the distribution was based on the lower limit of active rock glaciers. On the north-facing slopes of the Hohe Tauern (Lieb, 1991) and of the Tiroler Zentralalpen (verbal and written reports from Patzelt and Kerschner), the lower limit of active rock glaciers lies at about 2400m; on the south-facing slopes, it rises from 2500m in the east (Hohe Tauern) to higher levels farther west in the Tyrol. The problem is that many areas are lacking in rock glaciers indicative of discontinuous permafrost, and here other evidence, sometimes indirect, must be sought, such as basal winter snow temperatures, near-zero temperatures of spring water in summer, and seismic refraction surveys. The most detailed investigation so far has been carried out in the Ötztaler Alps (Haeberli and Patzelt, 1982). There are also unpublished investigations in the Dachstein area by Lieb, which led him to place the lower limit at 2300 m in the northern limestone Alps. The overall distribution of permafrost shown in Fig. 1.9 is based on such data, extrapolated linearly from area to area. Patches of permafrost too small to be drawn in detail are marked by dots.

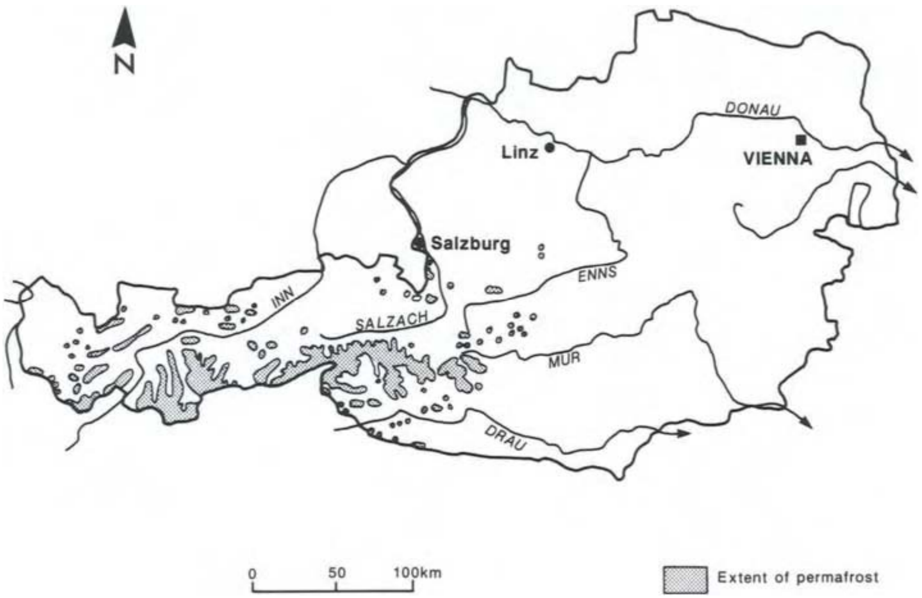

Fig.1.9. The distribution of discontinuous permafrost in Austria. Map compiled by G.K.Lieb

The existence of permafrost has caused many problems, often unsuspected, for the engineer. The problems have occurred in connection with the construction of high-altitude weather stations, military radar installations (permafrost encountered at 2640m on the summit of the Glungezer: Patzelt, 1983) and winter sports facilities. The latter include installations such as pylons for ski-lifts, access roads and tunnels, and large buildings (restaurants, etc.). Because the foundations of some of these encountered permafrost, there have been continuing difficulties which in some cases involved reconstruction. There are no publications or official reports on these problems, and it is often difficult to discover more about the exact problems involved because of reluctance on the part of the site owners to give more information. For only one site have more data been made available, kindly provided by Lieb, who obtained the information from the *Zentralanstalt für Meteorologie und Geodynamik*. This is the weather station at Hoher Sonnblick, 3106m. Here the bedrock is covered with loose material which is frozen the whole year below a depth of 0.3m. Engineering problems included:

- almost instantaneous refreezing of loosened material;
- after excavation for foundations, thermal equilibrium was not re-established for 2-3 years;
- formation of segregated ice near the permafrost table which required special measures;
- ground heaving and settling, necessitating the use of thermal insulation beneath the bases of structures.

As more and more experience is gained, and especially since about 1980, engineers and planners have become better equipped to anticipate and to deal with these problems, and structures built since then have so far been trouble-free.

9. Seismic activity

Austria is not to be regarded as in any sense a typical earthquake country; nevertheless it has experienced exceptional earthquakes of magnitudes similar to that of the Friuli event (6 May 1976). The eastern Alps, which occupy two thirds of the national territory, lie on the edge of the Mediterranean-trans-Asian earthquake belt, near to the border between the African and Eurasian plates, and the earthquake activity is predominantly linked to alpine tectonics.

Seismic activity in Austria is monitored by two bodies, the Earthquake Service of the *Zentralanstalt für Meteorologie und Geodynamik* since 1904, and the Earthquake Commission of the Austrian Academy of Sciences since 1896 which was absorbed into the Geophysical Commission in 1952. The broad picture of seismic activity in Austria has been studied especially by J.Drimmel, and the following account is based primarily on his work (see particularly Drimmel in Fink, 1986 and Drimmel, 1980).

All Austrian earthquake foci are located in the upper crust, mostly in the depth range 7-12km, exceptionally down to 20km. A striking characteristic of the stronger earthquakes in the eastern Alps is the form of the felt-area, which approximates to an elongated ellipse in which the long axis lies across the alpine trend and the earthquake epicentre corresponds to the southern focus of the ellipse. This means that the seismic waves are preferentially propagated towards the north and north-west and are frequently felt unusually far north in Bohemia and central Germany. The phenomenon was already known in the last century and led to the term *Transversalbeben* (literally, "transverse earthquake"), commonly used for eastern alpine earthquakes; a completely satisfactory explanation of this is still lacking.

Drimmel (1986) has prepared a map of areas liable to earthquakes in Austria (Fig. 1.10). It is based on historical and instrumental data for the period 1201-1982, and shows maximum epicentral intensities calculated on the Medvedev-Sponheuer-Kárnik = MSK scale (a detailed version of the modified Mercalli-Sieberg scale). Damage to houses

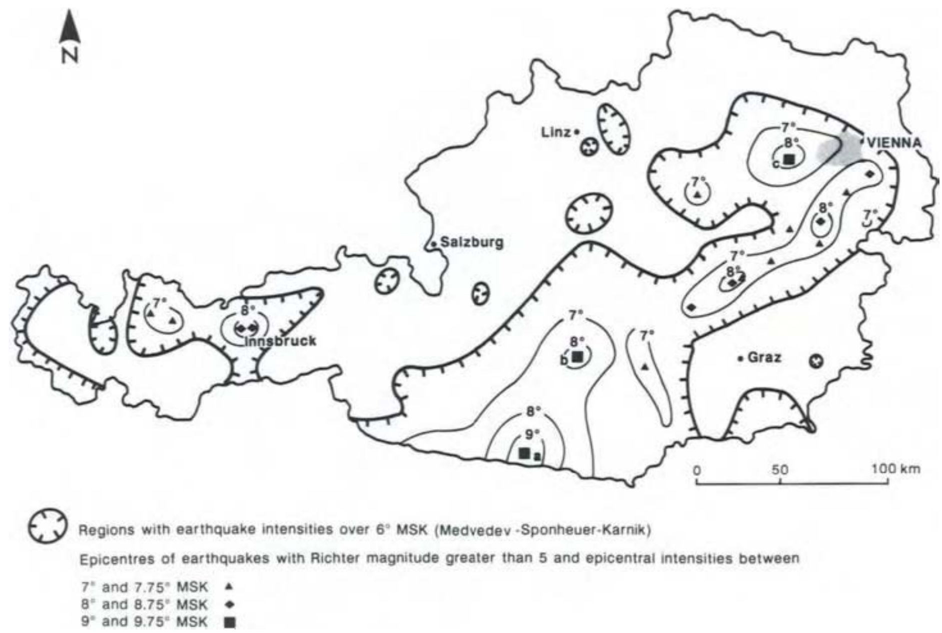

Fig.1.10. Areas liable to earthquakes in Austria, derived from maximum epicentral intensities of events between 1201 and 1982. *Source:* Fig.3.2 in Fink, 1986

in good conditions starts at about VI MSK; the distribution of earthquakes with such epicentral intensities forms the basis of Figure 1.10. For historical earthquakes, where the only information available concerns the area over which the disturbance was felt and the centre of maximum disturbance, it is possible to estimate the seismic energy and derive the Richter magnitude, and also to suggest the depth of focus. The epicentres of recorded earthquakes with the highest seismic energy (exceeding Richter M = 5) are marked on the map, as are corresponding intensity values.

On average, Austria has to expect an earthquake of epicentral intensity VIII or more every 46.3 years; earthquakes of epicentral intensity ≥VII occur every 8.5 years, and ≥VI every 1.6 years. The three most dangerous earthquake localities are, in order, Villach (A on Fig.1.10), Murau (B) and Neulengbach (C) with maximum epicentral intensities of IX-X and M = 6-6.5.

The most extensive Austrian earthquake area is related to the Mur-Mürz tectonic disturbance and the so-called *Thermenlinie* (hot spring line) of the Vienna basin. It forms a zone 30 ± 5km broad and 250km long, starting from point "B" on the map and stretching towards Vienna. Fifty per cent of all strong earthquakes occur in this zone. For example, there were major earthquakes at Murau in the Mur valley and Kindberg in the Mürz valley, and the strongest earthquake this century in Austria (M = 5.3) occurred 55km south of Vienna in the Vienna basin.

Another quarter of all earthquakes are located in Tyrol, the strongest around Innsbruck and Hall where the Wipptal disturbance meets the Inn valley tectonic line. Whereas the tremors associated with the Mur-Mürz and Vienna basin zones originate from foci at 8-12km depth (up to 18km at Semmering), those of the Innsbruck-Hall region tend to be slightly shallower (8-10km). There were also some very shallow tremors related to ground subsidence in the Hall salt-mining area.

The most potentially dangerous earthquake zone in Austria is connected with the Peri-Adriatic lineament, on which the so far most damaging earthquake of central Europe occured. This was the event of 25 January 1348 near Villach (point A on Fig.1.10), with an epicentral intensity of X and M = 6.5, similar to the Friuli event of 1976. Villach itself was partly destroyed by the tremors, and completely devastated by the consequential fires. The most sensational after-effect, however, was the huge landslide from the south slope of the Dobratsch. Together with the bursting of a lake formed behind the debris, it destroyed 17 villages, 3 castles and 9 churches. The year 1690 saw another event of almost equal magnitude, and another strong tremor hit the area in 1855.

A fourth slightly more dispersed group of earthquake foci extends along the northern border of the Alps, including Neulengbach (point C in Fig.1.10); west-south-west from here lies Scheibbs (the epicentre is marked on the map by the symbol for epicentres with intensities of VII-VIII) and, farther on, Molln (south of Linz). There is debate over exactly where the tectonic line responsible is located. The three foci occur in the crystalline basement underneath the alpine nappes on deep-seated disturbances which cannot be traced on the surface. Drimmel (1980) postulated that all three foci are associated with one and the same east-north-east to west-south-west trending lineament. Tollmann (1986) on the other hand connects the Neulengbach epicentre with the similar trending disturbance of the Mailberger fault system.

It should be mentioned that this scientific controversy generated considerable attention, because it became linked to the public discussion about Austria's first and (so far) last nuclear power station, for which a site north of Neulengbach had been chosen. In the end a plebiscite prevented the opening of the plant. For all that, scientists have never denied the seismic activity of the area, which lies in the impact zone of a dangerous *Transversalbeben* epicentre. The stumbling block to this project had been created much earlier by the planning board, which completely overlooked the possibility of an earthquake hazard when making the first decisions. The hazard, though, is obvious, even if the actual alignment of the fault responsible is unknown.

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BELGIUM

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1. Introduction

Research into natural hazards is attracting growing attention because of the increasing impact of natural disasters on economically developing areas, the greater levels of financial losses incurred and unacceptably high death tolls. In the 1980s, the FAO became interested in the problems of hazard mitigation, and later the United Nations moved actively into this field, especially with the initiation of the International Decade for Natural Disaster Reduction in the 1990s. At the same time, the International Geographical Union became closely involved in the occurrence and the geographical dimension of these morphodynamic phenomena.

On a world scale, the three major causes of devastation are earthquakes, floods and storms. In the last 20 years, some 3 million people have been killed by earthquakes: total earthquake damage for the year 1980 in Japan alone is estimated at 200 x 10^9 U.S.dollars, and for California at 50 x 10^9 U.S.dollars (Smolka and Berz, 1981). A single 100-year hurricane can cause losses of the order of 10 x 10^9 dollars, and even a "normal" hurricane such as Frederick in 1979 caused damage of 2 x 10^9 dollars. In 1992, about 500 types of natural hazard were registered on a worldwide basis. In the 1980s, about three times as many hazards were recorded as in the 1960s, which may reflect increasing incidence and/or better documentation. Insurance companies are directly concerned with such data and possible trends.

The investigation of hazards involves four aspects: classification, mapping, warning and protection according to Fournier d'Albe (1976). This Chapter will concentrate on the first two in the case of Belgium.

2. Types and classification of hazards in Belgium

Geomorphologically, Belgium lies in a comparatively stable and safe area from the point of view of earthquakes, volcanic hazards, tropical hurricanes and tsunamis. Nevertheless, it is still subject to numerous other types of hazard, some of which regularly recur. A detailed analysis of two newspapers over a 15-year period produced more exact data on type and frequency (Table 2.1) though clearly the data only include those events which were newsworthy at the time, and thus the total numbers may be under-estimated. There are about 150 incidents mentioned in the period 1979-93, which gives an average of ten per year. The most important problems are coastal erosion and sea defences (42), flooding (30) and storm damage (14). The figure for earthquakes (19) includes events with a low seismic intensity which caused no damage, but which nevertheless found their way into the newspapers because of their news value: the figure is thus an over-estimate in comparison with the other types.

Table 2.1. Classification and frequency of hazards in Belgium based on press reports in two newspapers, *Het Nieuwsblad* and *Het Laatste Nieuws*, 1979-93

Summary:

Earthquakes	19	Subsidence	
Mass movements	11	in karst areas	1
Soil erosion	5	in marl areas	15
Floods		in coal-mining areas	5
due to rainfall	30		
due to snowmelt	1	Storms	14
due to high tide	7	Coastal erosion	42

Total number: 150

Annual frequency, 1979-93

	1979	80	81	82	83	84	85	86	87	88	89	90	91	92	93
Earthquakes	-	1	1	2	4	1	3	-	1	-	-	-	-	5	1
Subsidence															
(a) marl areas	1	2	2	3	-	-	-	-	1	4	-	2	-	-	-
(b) coal areas	2	1	1	-	-	-	-	-	-	-	1	-	-	-	-
Mass movement	-	-	1	-	2	-	3	1	-	1	1	-	1	1	-
Soil erosion	-	-	-	-	-	-	2	1	-	-	-	-	1	1	-
Floods (rain)	1	4	3	3	1	-	2	5	1	1	-	1	1	5	2
Floods (melt)	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-
Floods (tide)	-	2	-	-	-	-	-	2	-	-	-	3	-	-	-
Coast erosion	-	1	4	-	1	1	-	3	-	8	10	8	1	3	2
Storms	-	-	-	2	-	1	-	-	-	-	-	6	3	2	-
Totals:	4	11	12	10	8	3	10	11	3	9	10	18	7	17	3

3. Earthquakes

Seismic activity has been studied in detail since 1985 by the Royal Observatory of Belgium (Uccle, Brussels). Before that date information is quite scarce. The maximum magnitude on the Richter scale is 6 and the maximum epicentral intensity VII. Earthquakes with a focus shallower than 30km and M ≥5.5 have not caused significant surface displacement and the number of damaging events is very small. Investigations have been conducted by Ahorner *et al.* (1975), Alexandre (1985, 1989), Camelbeeck (1984, 1993), Camelbeeck and De Becker (1985), Demoulin *et al.* (1992), Fourmarier and Legraye (1926), Fourmarier and Somville (1926), François *et al.* (1987), Haessler (1985), Jones (1964), Melchior (1984), Pissart and Lambot (1989), and Van Gils and Zaczek (1978).

3.1. Seismic activity in historical times

Prior to the 19th century, only relatively few shocks were recorded (16 in the period 400-1599, 32 between 1600 and 1899), of which the main ones are given in Table 2.2.

For the decade 1961-70, 195 earthquakes were recorded altogether, of which 25 per cent were felt by the population.

3.2. Geographical distribution of earthquakes

Figure 2.1 from Ahorner *et al.* (1975) shows the most seismically active zones, expressed in Mercalli intensities. Two lineaments dominate: an east-west axis corres-

Table 2.2. Principal earthquakes in Belgium, 1395-1992

1395	(11 June), epicentre unknown
1690	Aachen
1692	Tienen (epicentral intensity VI)
1714	Tienen
1755	Düren (25-26 December)
1828	Tienen (5 tremors)
1911	northern border of the Eifel (15 tremors)
1938	Zulzich (11 June; 7 tremors)
1949	Havré (3 April; 12 tremors)
1965	Strepy-Bracquenies (15 December; 7 tremors)
1966	Chapelle-lez-Herlaimont (16 January; 84 tremors)
1967	Carnières (34 tremors)
1968	Haine-St Pierre (58 tremors)
1973	Herzogenrath (9 tremors)
1983	Liège (8 November)
1992	Roermond (13 April)

ponding to the Brussels-Liège line, and a north-west to south-east axis from Eindhoven to Aachen. Four seismically active zones can be identified: the Henegouwen basin, the Brabant-Flanders massif, the Liège region, and the Eifel region together with the Roer graben. The maximum intensity is VIII, and the return period for epicentral intensities ≥ VI, calculated for the last 350 years, is 16 years.

There is a relatively high number of shocks in the synclinal Henegouwen basin (23 ≥ V), the foci lying at depths between 3 and 6.5km; two fault systems, the Faille de Bordière and the Faille du Midi, play a crucial role. In contrast, the Cambrian-Silurian

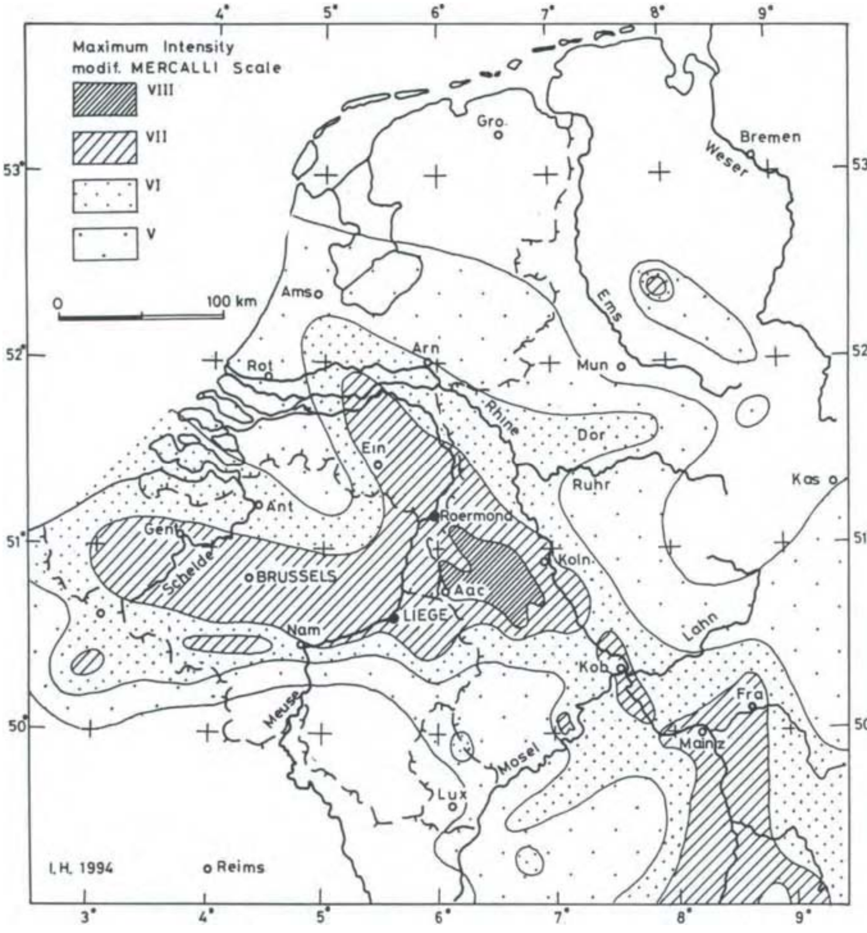

Fig.2.1. Earthquake intensity distribution (modified Mercalli scale) in Belgium (after Ahorner *et al.*, 1975)

block of the Brabant-Flanders massif is characterised by deeper-focus shocks (10-27km depth). The Liège region partly resembles the Henegouwen basin, influenced by the Faille du Midi, with relatively shallow earthquakes (8 ≥ V). The Eifel is the most active zone (45 shocks, foci 5-10km deep, increasing to 15km in Limburg), associated particularly with the Roer (Rur) graben and with fault lines such as the Feldbiss.

3.3. Recent earthquakes

The Liège earthquake of 8 November 1983 was classified as 4.9 on the Richter scale, maximum epicentral intensity VII at Ans-Vottem, depth of focus 4km. It was felt as a heavy shock owing to reactivation of a fault line along 1km and surface deformation of up to 0.3m. Tectonically, the Liège region represents a zone of higher risk owing to the intersection of the two lineaments already referred to (3.2). The 1983 event was the most severe in Belgium since that near Oudenaarde in 1938 (M = 5.6). Two people were killed, 32 injured, and with the high number of houses damaged or destroyed, the area was declared a disaster zone. More detailed analyses are given in Camelbeeck and De Becker (1984, 1985), François *et al.* (1987) and Haessler (1985).

The Roermond earthquake of 13 April 1992 was also noteworthy (M = 5.5). Its epicentre lay about 10km outside Belgium in the Campine region of the Netherlands. Its focus at a depth of 16km is related to the Peel fault of the Roer (Rur) graben. About 200 aftershocks were recorded. Earthquakes of this intensity occur 1900 times a year worldwide, but for the Benelux countries the return period is 130 years. Damage totalled 7×10^9 Guilders (about 3.7×10^9 U.S.dollars), and the event was considered a national disaster in the Netherlands, though not in Belgium despite the mass movements that were triggered and the damage to some of the Meuse dykes (Fig.2.2). Sand fountains (sediment liquefaction under pressure) were also reported.

4. Subsidence

4.1. Subsidence by karst processes

Hazards related to limestone solution in Belgium are seldom mentioned, but they exist. Theoretically, in all limestone formations outcropping or near the surface, caves can develop and subsequently collapse, especially in the limestone fringe along the north of the Ardennes and in the Condroz region. No such collapses in these areas have been reported in the last 15 years. There is, however, one small region (100km^2), near Doornik, traversed by the river Scheldt, where surface collapses have occurred. The area is partly underlain by limestones with a cover, several metres thick, of Mesozoic marl, Tertiary sands and clays and Quaternary loess. The Scheldt loses part of its flow into the limestone at the "Trouée à Kain". Collapse of subsurface caves in the limestone has led to various forms of ground subsidence; circular or oval cavities or depressions are up to 20m in diameter and some metres in depth, depending on the thickness of the

Fig.2.2. Damage to dykes along the Meuse caused by the Roermond earthquake of 13 April 1992 centred in the Campine area of the Netherlands

overlying deposits, and some have vertical sides. Subsidence appears to be continuous but occasional sudden collapses also occur, generally unpredictable but mostly during the wetter conditions of December, January and February. Lowering of groundwater levels also appears to accelerate the processes. In May 1984 about eight pits were formed; the total number of cavities formed between 1955 and 1983 is approximately 100. The city of Doornik must suffer from this type of underground disturbance but no evaluation of the damage is available. Maps published by Delattre (1985a) and Gulinck and Legrand (1968) show the geographical distribution of the known pits, and several papers have described this type of hazard (Calembert, 1946-47; Camerman, 1954; Delattre, 1985; Delecourt and Marlière, 1938; De Roubaix and Legrand, 1977; Derycke, 1979; Ek, 1976a, b; Laurent, 1985; Lefevre and Legrand, 1964; Lefevre *et al.*, 1967; Quinif,1977; and Quinif *et al.*, 1985).

The region of "Land van Herve" is also liable to karstic subsidence. Here, the limestone is overlain by Mesozoic chalk, Tertiary clays and sands, and Quaternary loam

(Calembert, 1952; Evrard, 1945, 1950, 1951, 1957-58). Some villages have suffered from subsidence caused by complex underground collapse; but also here the influence of earthquakes cannot be excluded.

Natural depressions in loess areas without any soluble subsurface formations have also been mentioned in the literature, in Leefdaal (Gullentops, 1952) and in Doncelles in Hesbaye (Dudal, 1955). They may be caused by subsurface piping, i.e., removal of fines by groundwater flow and slow subsidence of the surface above.

4.2. Subsidence owing to marl excavation

Marl digging has been going on in parts of Belgium (the areas of Zichen-Zussen-Bolder, Riemst, Kanne and Hoegaarden), as well as in the Netherlands (Maastricht, St Pietersberg), since the seventeenth century. Complex networks of tunnels up to 3m wide and 4m high, excavated above the groundwater level, have been created by extraction of marl, and are still in use for mushroom growing. Despite the roof thickness being as much as 15-16m, collapse and surface subsidence regularly happen in the Muizenberg. Pits up to 30m in diameter and 5m deep are forming, damaging infrastructure, houses and roads. No less than 15 reports of such disturbance appeared in the newspapers in the period 1979-93 (Table 2.1). Earlier reports appeared in 1952, 1958 and 1966. The Roosburg event of 1958 was the most disastrous, when 18 mushroom workers were killed by tunnel collapse. The community of Riemst has started a mapping project of the tunnel labyrinth in their area. There appears to be a close correlation between tunnel collapse and the intensity of precipitation.

4.3. Subsidence owing to coal mining

Coal is mined in the Campine region which includes the districts of Beringen, Zolder, Houthalen, Zwartberg, Winterslag, Waterschei and Eisden. The depth to the coal seams is about 500-1000m and, since production began, about 679 million m^3 of material have been removed. Average subsidence at the surface owing to roof collapse in the mines can be as much as 8m; its pattern reflects that of the mining and the sizes of surface depressions closely correspond to the volumes of material extracted underground. Morphologically, the surface relief is completely changed.

The Zuidwillems canal crosses such an area of subsidence; in this section, its dykes have had to be raised by up to 8m above the surface to maintain the water level in the canal. Many of the subsidence depressions would normally be flooded, but groundwater pumping by 30 pumping stations keeps the water table artificially low to prevent this. The direction of flow of some streams has been reversed in this process (Van Steelandt, 1993).

During the period 1979-93, there were five reports of damage caused by mining subsidence in the press. A special Mine Damage Service run by the Campine Coal Mining Company handles claims for compensation for damage to buildings, roads and other infrastructure. In 1988, about 490 claims were dealt with, about 100 fewer than in the previous year. In the future, the number of claims will also diminish and it is expected that subsidence will cease about 10 years after a mine is closed. The distribution of damage claims in 1988 was as follows: Zolder 291, Eisden 56, Waterschei 53, Winterslag 46, Beringen 44.

Similar subsidence problems undoubtedly exist in Wallonia in the Borinage, and in the Liège basin.

5. Mass movements

In the hilly regions of Belgium, mass movements such as rockfalls and landslides are fairly common. The majority go unreported in the newspapers because they do not impinge on human activities: the total of 15 mentioned in the press for 1979-93 is certainly an under-estimate.

Rockfalls and rock failures are related to bedrock outcrops and steep slopes in the Meuse valley and its tributaries. Calembert (1947-48) described a good example in Flémalle and Huy on 1 December 1946, known as the "Château de Chokier". A 7000t block became detached and obstructed the railway for six weeks. Unplanned rockfalls also occasionally occur in man-made excavations such as in Namêche, Leuven and Rotselaar.

Landsliding and debris flows are most commonly encountered in the Flemish Ardennes, built of alternating horizontal layers of Tertiary sands and clays. Numerous springs and seepage zones, together with the steepest slopes to be found in the northern part of Belgium, promote instability. In places, roads and railways have been blocked and interrupted: examples are given by Calembert (1947), Halet (1904), Lefevre (1926-27) and Van Maercke-Gottigny (1980, 1981). Flows in saturated colliery waste have occurred following intense rainfall, as in Jupille in 1961 where 11 people died, buried in the waste; 17 houses and 166 apartments were damaged.

River banks, scarps, dykes, artificial road cuts are regularly destabilised by slumping and local collapse. Internal cohesion is reduced following heavy rain, but periods of drought and lowered river levels can also result in subsidence. The 1992 Roermond earthquake, already described, similarly caused slumping of dykes (Fig.2.2).

6. Soil erosion

During and following heavy rainfall events, bare land in many hilly regions is subject to sheet wash, rilling and sometimes gullying. This type of soil erosion is especially common in the loamy regions of Middle Belgium after harvest and during ploughing. There have been many detailed studies of the phenomena. The Pedology Department of the University of Gent under the direction of R.Tavernier was particularly active in the soil mapping of the whole of Belgium, and in the course of this work noted the incidence of soil erosion processes. J.De Ploey and his co-workers in the University of Leuven have also studied such morphodynamic processes in the loam regions (De Ploey, 1986; Poesen, 1989, 1993; Poesen and Govers, 1990; Savat and De Ploey, 1982). As well as surface rilling, two other types of hazard may appear: the formation of ephemeral gullies and of deep permanent gullies with steep sides.

Fig.2.3. A (*upper*): Erosion of the humic topsoil by rilling in an area of sandy loam; potato crop; B (*lower*): Sandy loam colluvium burying the humic topsoil at the foot of slopes (Photos: I.Heyse, 1985)

Ephemeral gullies can form and re-form up to seven times a year. The rates of incision can be 1-10mm/year, and a single intense cloud burst of 10 minutes' duration and several centimetres of rainfall has been observed to erode 30t of loam per hectare. Sometimes the entire Ap humus horizon is destroyed or buried (Fig.2.3). Deep, steep-sided, permanent gullies (Fig.2.4) change the morphology completely and may in turn induce mass movements.

Financial losses owing to soil erosion have been estimated in the range between 1 and 2 x 10^9 Belgian francs (about 15-30 million U.S.dollars) in a year by de Ploey. The news value of this type of hazard is very low because it seldom shows clearly visible signs or affects infrastructure; the danger is long-term and insidious. Figure 2.4 shows the irreversible loss of soil by improper cultivation techniques.

Fig.2.4. Formation of deep vertical-sided gully, showing side slumping, owing to improper cultivation techniques in a hilly area of sandy loam (Photo: I.Heyse, 1993)

7. River flooding

According to Table 2.1, 30 significant flood events caused by high rainfall have taken place in the 15-year period 1979-93, an average of two per year. Such a figure is likely to be an under-estimate because, for example, it is known that the city of Dendermonde alone has experienced 16 river floods a year during the period 1941-92. In the case of major river flood catastrophes, there is probably on average one every 20 years. The most important and serious river floods in Flanders and Wallonie during the last 15 years are listed in Table 2.3.

Different types of river flood may be distinguished according to the primary cause: prolonged winter rainfall, prolonged summer rainfall, intense thunderstorms, excess karst water discharge, snow and ice melting, and enhanced surface runoff over frozen ground.

Table 2.3. Dates of principal river floods in Flanders and Wallonie

3 April 1980
21 July 1980: return period 150 years, peak discharge of the Meuse $2550m^3/s$
16 April 1985
10 June 1985
1 April 1986
2 March 1987
23 December 1991
11 and 18 August 1992
12/13 January 1993
22/27 December 1993: see section 7.1 below. Meuse peak discharge $3650m^3/s$
Major river floods in earlier times:
10 January 1926: Meuse peak discharge $3500m^3/s$, before 1993 regarded as the flood of the century
15 February 1966: Meuse peak discharge $2200m^3/s$
3 January 1967: same discharge peak
23 February 1970: same discharge peak

7.1. River flooding caused by excess winter rainfall

Heavy winter rainfall leading to flooding is often associated with the passage of deep depressions across western Europe. Two examples will be given:

The flooding of 10 January 1926 was until very recently considered the most disastrous of the twentieth century in the Meuse basin. At this time, the city of Liège had not yet been protected by river dykes, and when the river level rose to more than 4m above normal, large areas of the city were inundated: in places, water was more than 1.5m deep in the streets. The peak discharge of the Meuse reached $3500m^3/s$, some ten times its average flow. Conditions in the city became chaotic: food could only be supplied by train and even newspapers failed to appear. Soon after this disaster, a dyke-building project was undertaken.

The flood of December 1993/January 1994. Throughout much of western Europe, river discharges reached record levels at this time, associated with a series of large depressions. In Belgium, severe flooding affected the Meuse, Scheldt and Yzer basins

(Figs.2.5 and 2.6). In the Meuse basin, the whole river system from the French to the Dutch border was affected. In Dinant, water rose to more than 2m in the streets, the brand new Walloon Parliament building in Namur was flooded, and in Seraing near Liège, the water level reached 4.72m above normal, which corresponds to a discharge of $3650m^3/s$. In the Campine area, the maximum flood level occurred in the night of 22/23

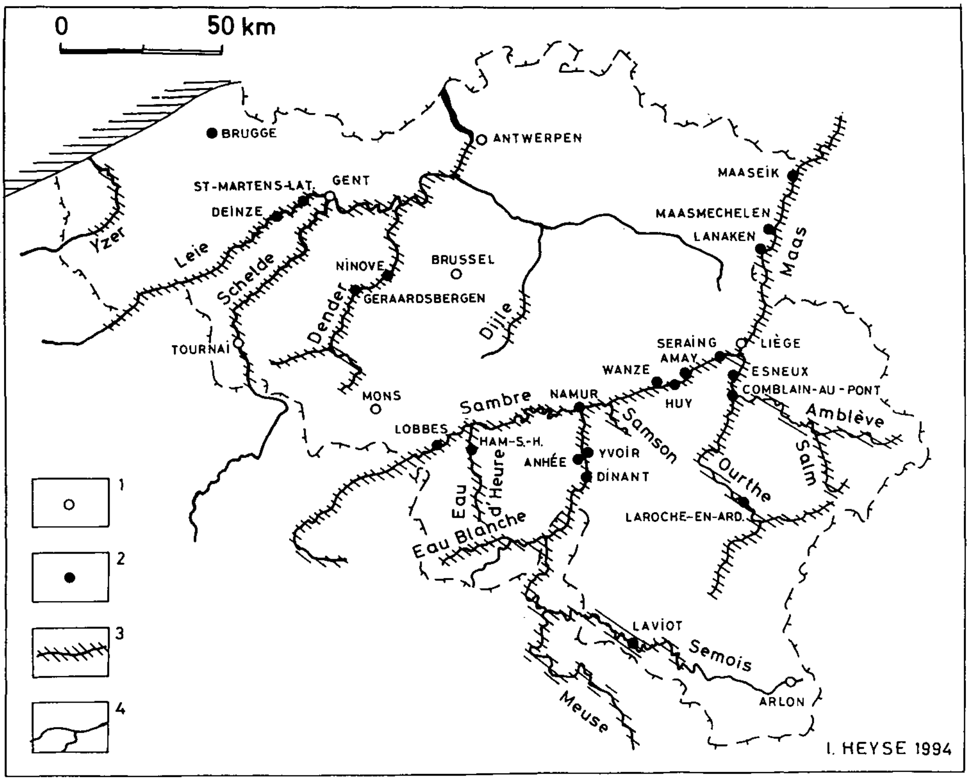

Fig.2.5. Map showing extent of flooding in the Meuse, Scheldt and Yzer basins in December 1993/January 1994. 1. Main towns for location purposes; 2. Settlement affected by serious flood hazard; 3. Flooded valleys; 4. Rivers

Fig.2.6 (*facing page*). A (*upper*): Flooding in the Campine area of the Meuse valley, near Maastricht; B (*middle*): Dyke burst, Meuse valley, Stokkem, Molenveld: note the lateral shifting of about 2m in the rebuilt dyke caused by water pressure; C (*lower*): The Yzer-Ieperlee confluence where a lake covering 7000ha was formed. All three photos by I.Heyse in December 1993.


IJzer

December 1993, 5m above normal, with a discharge ten times the average winter flow and 100 times the average summer flow. The dyke-building programme begun in 1980 was only 20 per cent completed, and the water-soaked loamy dykes were not able to withstand the water pressure. About 2500 people had to be evacuated.

In the Scheldt basin, it was the upper Scheldt and the Lys that were worst affected. Much of the Lys water found its way through the Schipdonk canal and the Gent-Bruges canal, threatening the city of Bruges (the "Venice of the North") which only narrowly escaped a major catastrophe (as in the case of Köln in Germany at the same time). The Deinze-Gent section was entirely inundated and the dykes of the lower Scheldt were only just able to cope with the water at bankfull stage.

The water level of the Yzer south of Diksmuide reached 2.36m above the normal winter level (53m^3/s) and in some places overtopped the dykes. The plain around the Yzer-Ieperlee confluence was transformed into an immense lake covering 7000ha. Evacuation of this water faced severe difficulties because of the low-lying coastal plain between this point and the sea, and was only possible during low tide. As a result, much farmland remained flooded for a month.

7.2. Flooding linked to cyclonic summer rainfall

The flooding of 21 July 1980 provides a good example of this type; according to Laurent *et al.* (1980), it has a return period of 150 years. Over the whole of the Meuse basin, precipitation averaged 109mm: such a figure has only been exceeded three times during the period of record: 1888 (167mm), 1930 (171mm) and 1942 (197mm). The maximum recorded intensity was 70mm in 24 hours, and peak recorded rainfall was 216mm compared with a normal value of 90mm. The result was flooding of an area covering 20 000km^2 and a river discharge rising to 2500m^3/s. Rivers in the neighbouring Scheldt and Lys catchments also experienced flooding at this time.

7.3. Flooding associated with summer thunderstorms

Isolated cloudbursts caused by convectional instability can be quite frequent in summer, but their locations are difficult to predict. An example occurred on 6 June 1985 near Ouwegem-Asper, south of Gent (Fig.2.7). Other factors that contributed to the flood apart from rainfall intensity were an impermeable clay layer at shallow depth, causing rapid soil saturation, and hilly relief assisting rapid runoff.

7.4. Flooding on karst-fed streams

High surface discharges from streams in karst areas can result from insufficient capacity of swallow holes and underground passages. Such a situation arises from time to time on the Lesse river which flows across an anticline of calcareous rock; normally it passes into the Han sur Lesse caves, but during high flows water is forced to utilise an older Lesse valley system known as La Chavée.

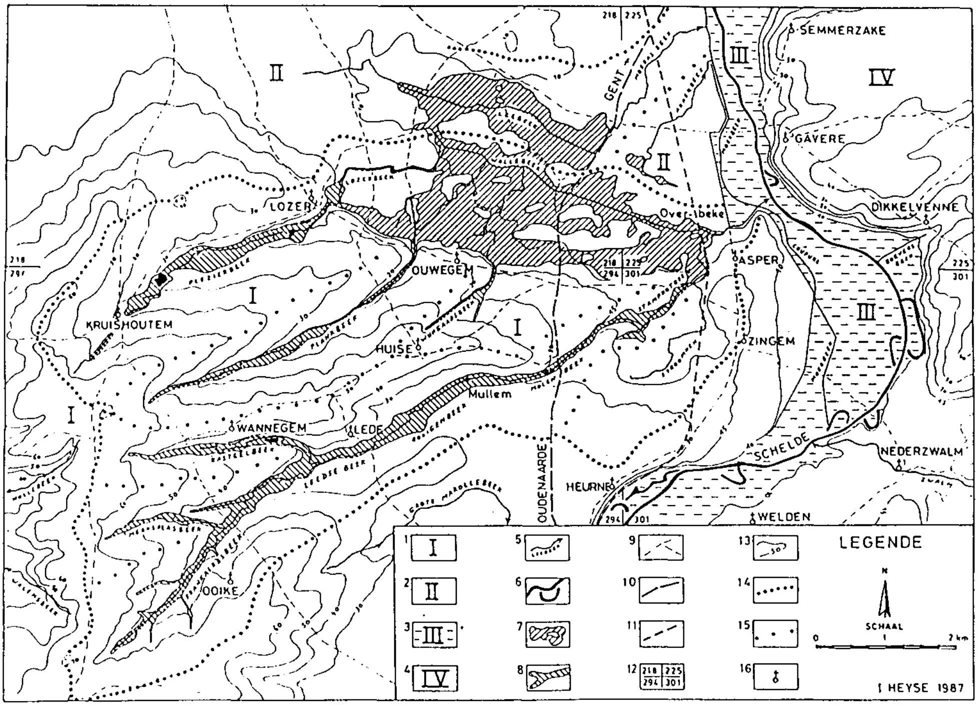

Fig.2.7. Map of small-scale flooding in the basin of the Wallebeek Ouwegem-Asper caused by the thunderstorm of 6 June 1985. Floodwater crossed a low watershed in region II. *Regions*: I. Hilly interfluves in the Wallebeek basin; II. Flemish valley plain; III. Scheldt alluvial plain; IV. Hilly region. *Other symbols*: 5. Streams; 6. River Scheldt; 7. Flooding in the flat area; 8. Flooding in the hilly area; 9. Minor roads; 10. Motorway Gent-Oudenaarde; 11. Secondary roads; 12. Topographical maps: sheet numbers; 13. Contours (10m intervals); 14. Main watershed of the Wallebeek basin; 15. Secondary watersheds; 16. Church

7.5. Floods related to snow and ice melting

The rapid melting of a thick snow cover can be considered to represent the postponement and concentration of earlier precipitation, and has the same hydrological effect as intense rainfall. Such spring snowmelt floods are more frequent in the Meuse catchment than in the Scheldt because of the greater amounts of snow that fall in the Ardennes, where there is an annual average of 5 to 10 days snow cover of 20cm or more.

Melting of river ice and ice-jam formation is a phenomenon following prolonged periods of winter freezing. In shallow or narrow channel segments, and upstream from bridges or other obstacles, the break-up of the ice into ice rafts can jam the river and lead to very rapid rises in water level; subsequent freezing can further consolidate the ice jam. Weather conditions in January 1985 favoured such events in the Meuse valley near Namur and on some tributaries such as the Semois near Vresse (Figs.2.8 and 2.9). Ice jams developed on the 5th, 6th and 9th of January, with water levels rising quickly to 3m above normal winter level, dropping back to normal levels between each episode of freezing. In the Scheldt basin at this time, similar phenomena were observed on the Durme and Dender valleys (between Geraadsbergen and Ninove).

Fig.2.8. Ice-jam formation, Semois valley, Ardennes, in 1985 (Photo: I. Heyse)

7.6. Flooding resulting from ground freezing

The impermeability of frozen soil acts to prevent infiltration in the same way as paved urban areas. Mudflow and creep processes are also enhanced for the same reason. Flooding of this type occurred in the Lys basin on 26 January 1985, and previously on 3 January 1965. In 1985 302 houses and four factories near Kortrijk were flooded.

Fig.2.9. Ice-jam formation in the Meuse valley near Namur in 1985 (Photo: I. Heyse)

8. Coastal flooding

Despite the attention that is now being paid to the present-day risks of flooding, the threat of coastal inundation is not a new one. The historical transgressions during the fifteenth century, known as Dunkirk III, played a major role in the formation of the entire Scheldt estuary, as did earlier transgressions (Dunkirk, Flandrian) in the evolution of the Belgian coastal plain as a whole (Ameryckx, 1959) and in the history of its occupation by man (Thoen, 1978). In the seventeenth and eighteenth centuries, flooding was purposely undertaken for military (strategic) reasons, as in the defence of the city of Ostend. It was also employed during the 1914-18 War in the Yzer basin to separate the military frontlines. In theory, it would be possible, if necessary, to flood the whole of the coastal plain lying below 5m.

In Belgium, tidal water is present only in the estuary of the Scheldt, the lower Scheldt and in some tributaries. At Flushing, the Scheldt estuary is 5km broad but narrows rapidly inland (Antwerp (75km inland): width 400m; Rupelmonde (90km): 250m). The mean tidal range is 3.66m at Flushing, 4.67m at Antwerp and 1.76m at Gent which is close to the tidal limit. The tidal maxima and minima in the Scheldt are:

Flushing	+6.95m	-0.93m
Antwerp	+7.85m	-1.17m
Dendermonde	+6.83m	-0.55m
Gentbrugge	+6.42m	-1.55m

(All figures refer to NKD, Nul Krijgs Depot (Zero Military Level), which is 0.08m lower than the datum used for the Second General Levelling).

The data show that the maximum high tide levels are attained not at the river mouth but farther inland, in the Antwerp-Dendermonde section, and this is the reason why the greatest potential flood risk is in the alluvial plain of the lower Scheldt (Mys *et al.*, 1983). To reduce the risk of flooding, a system of dykes has been built, together with a series of overflow polders to store excess water during storm surges. Some parts of the Scheldt tributaries are also tidal, for example the Durme to Lokeren and the Dijle to Haacht.

Claessens and Belmans (1984) define "normal" storm surges as those that reach 6.5 - 7.0m above NKD at Antwerp. "Extraordinary" storm surges attain levels greater than 7m. Important storm surges are always related in Antwerp to the top of the quay (7.0m NKD, called the "blue stone level"). Table 2.4 lists some important storm surges this century.

Table 2.4. Dates of the most important storm surges, 1906-1986

Date		Water level attained (m NKD)	Comments
12 March	1906	7.15	
13 January	1916	7.02	
26 November	1928	7.15	
23 November	1930	7.30	
7 April	1943	7.03	
1 March	1949	7.08	
1 February	1953	7.85	The storm surge of the century; damage estimated at 595 x 10^6 BF(approx. 17 x 10^6 U.S.dollars)
23 December	1954	7.11	
10 December	1965	6.99	
16 November	1966	7.03	
14 December	1973	7.10	Damage repairs cost 105 x 10^6 BF
3 January	1976	7.31	Known as the Ruisbroek flood; damage 865 x 10^6 BF
15 November	1977	7.24	Repairs cost 187 x 10^6 BF
11 November	1982	7.39	
2 February	1983	7.07	
24 November	1984	7.14	
20 October	1986	7.20	

8.1. The storm surge of 1 February 1953

Affecting vast areas of the lowlands of Belgium and the Netherlands, this was the most disastrous storm surge flood of the century. Beginning on 31 January and lasting until 2 February, it included three high-tide periods. All sea defences in Belgium, the Netherlands, north-west Germany and eastern England were severely tested, with

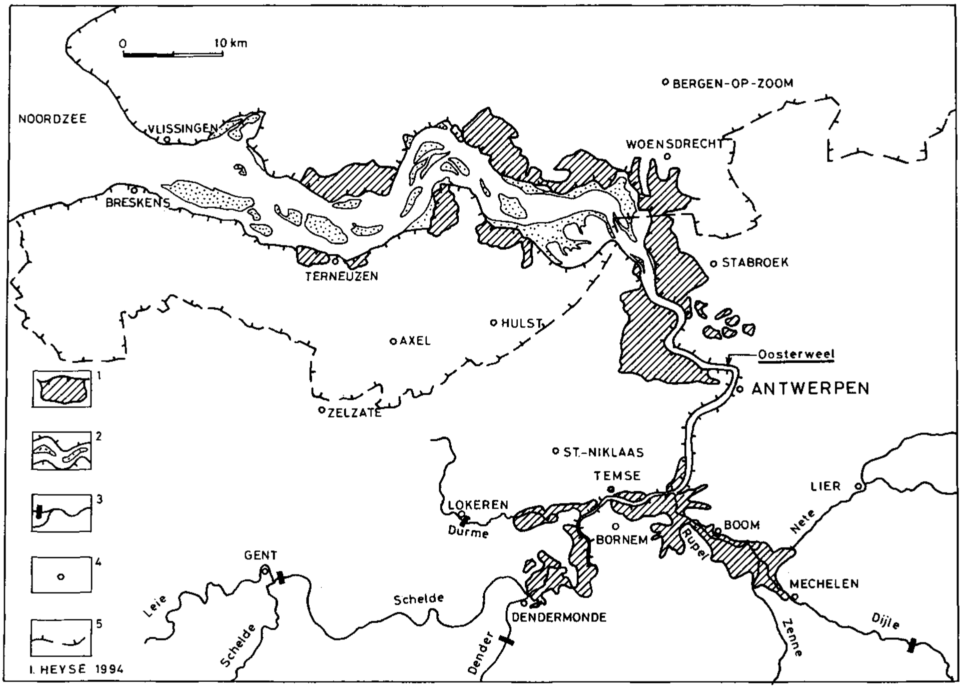

Fig.2.10. Map of the areas around the Scheldt estuary flooded during the storm surge of 1 February 1953. 1. Flooded area; 2. Scheldt estuary with sandbanks, main dykes and sea defences; 3. Rivers and tidal limits; 4. Towns; 5. Border to the Netherlands

extensive damage in places and hundreds of breached dykes. The north-westerly gales forced water into the funnel-like estuary of the Scheldt, causing the level to rise by 2.5m above normal high tide. The average water set-up for Belgium was 2.3m, compared with 3m for the Netherlands. In Antwerp, the water level rose 85cm above the blue stone level of the quay (Table 2.4). There were 43 dyke breaches downriver from Antwerp, and 180 above it, as well as 30 cases of dyke subsidence, in particular near the Rupel-Scheldt confluence (the lowest part of Belgium). The return period of the flood was estimated at about 100 years. In the Scheldt basin, 24 000ha were flooded, of which 9000ha lie in the Netherlands. There was additional flooding around Antwerp, Hoboken and Hemiksem. Figure 2.10 shows the extent of inundation around the Scheldt estuary.

8.2. The storm surge of 10 December 1965

This provides a good example of the interaction between tidal effects and river discharge. On this occasion, because of the coincidence of the surge with high river discharge on the Scheldt (reaching 258m^3/s), water levels in Dendermonde rose to the 1953 reference level and even to 20-30cm above it farther upstream. At Antwerp, however, the level was actually 86cm below that of 1953, and below Antwerp, as much as 1m lower than in 1953.

8.3. The SIGMA plan

In the period 1891-1970, mean high-water at Antwerp has risen from 4.68m to 5.24m (= 0.56m) or about 6cm every decade on average. In some parts of the Scheldt basin, the rise is even greater - up to 1.4cm/year at the river Durme (De Leenheer, 1966). The tidal range in the Scheldt estuary has also increased by 0.8m. Furthermore, the number of major storm surges has risen from 5 at the beginning of this period to 42 at the end. All these rising trends are especially marked in the last three decades, which has prompted the Government to re-evaluate the safety of the whole area of Belgium that lies below high tidal surge levels, and of Antwerp in particular. Statistically, a water level of 7.5m in Antwerp (50cm above the blue stone quay) has a return period of 50 years; a water level of 8.0m may be expected every 200 years, and of 8.5m every 1000 years. Allowing an extra 2m for exceptional north-westerly storms and a further safety margin of 1m, it is concluded that the dykes in the entire Scheldt basin should be designed for a level of +11m NKD in order to protect against the 200-year flood.

This is the basis of the SIGMA plan, a construction programme to strengthen and raise 480km of dykes. Raising of the dykes will cost 22 x 10^9 BF (about 640 x 10^6 U.S.dollars), and construction of flood-control polders and a storm-surge barrier in the estuary would cost a further 35 x 10^9 BF (about 10^9 U.S.dollars). Because of local circumstances (presence of industry, type of infrastructure, lack of space, present arrangement of the dykes, etc.), the work programme and some of the objectives have had to be modified as follows:

Dykes to be raised to 11m: section downstream from Oosterweel
to 8.35m: section between Oosterweel and the Temse bridge
to 8.00m: section between Temse bridge and Schoonaarde
to 7.50m: section between Schoonaarde and Gentbrugge

After the 1976 flood, a yearly budget of 2 x 10^9 BF was adopted to implement the Sigma plan; by 1991, about 75 per cent of the work had been completed, though the storm-surge barrier at Oosterweel has been cancelled because of its excessive cost.

9. Coastal erosion and sea defences

The last few decades have seen the publication of numerous studies dealing with the dynamics of the Belgian coastal environment (e.g., Baeteman, 1977, 1989; Baeteman *et al.*, 1992; De Moor, 1981, 1988, 1991; De Moor and Blomme, 1988; De Moor and Heyse, 1974, 1975, 1979, 1981; Heyse, 1979a, b; Houthyus *et al.*, 1993; Lebbe and Walraevens, 1989; Tavernier, 1947; Tavernier *et al.*, 1970; Thoen, 1978). As well as the marine transgression studies, there is increasing interest in the present-day interactions of beach and offshore processes.

With a length of 65km, the Belgian sandy coast is built up by marine and aeolian processes to form a coastal barrier stretching from near Dunkirk to Breskens. About 35km of this length has been artificially strengthened with sea walls (dykes), 27km consists of natural sand dunes, and 3km comprises man-made infrastructures such as harbours. For all except the last category, there is a continuous sandy foreshore several hundred metres in width, consisting of medium sand and affected by a semi-diurnal asymmetrical tide of 3.9m amplitude and a tidal cycle of 12h 27min. The tidal data for Ostend are as follows:

Mean low water spring tide:	+ 0.02m
Mean low water neap tide:	0.75m
Mean high water neap tide:	3.78m
Mean high water spring tide:	4.65m
Extreme high water spring tide:	5.08m
Storm-surge warning level:	5.60m
Dangerous storm-surge level:	5.90m
Maximum recorded level (1:02:1953):	6.66m

The present rate of sea-level change along the Belgian coast is about 10cm per century (rise of sea level with respect to the land). Dyke elevation varies from 8.6m at Ostend to 11m at De Haan and Zwin.

9.1. Problems of beach erosion

The coastal sections where erosion of the sandy beach is most pronounced are De Panne-Koksijde, Lombardsijde Westende, Raversijde, Klemskerke-De Haan and Knokke-Heist. Several techniques are used to combat beach depletion: sand supplementation, anti-erosion devices, underwater anti-erosion berms and Longard pipe networks. At De Haan, beach feeding over a length of 2150m has already restored a volume of $1.4 \times 10^6 m^3$, but against this, a single storm can easily remove 40 $000m^3$. In 1990, a series of nine winter storms eroded a total of 250 $000m^3$. The costs of future anti-erosion measures at De Haan are estimated at 1.5×10^9 BF. At Knokke, artificial beach restoration involving the supply of $9.3 \times 10^6 m^3$ of sand has cost 2.3×10^9 BF.

Detailed research on the sedimentary dynamics of the Belgian coast conducted by De Moor and others during the last 20 years shows that there are eight segments of the coastline undergoing erosion: Koksijde, Nieuwpoort-Lombardsijde, Middelkerke, Raversijde, Ostend, De Haan, Blankenberge and Knokke, intercalated with six segments that are aggrading and nine that are stable.

9.2. Dune erosion

From 1947 to 1993, air photos show that the dune front has receded by 15-30m, an average of 0.33-0.65m per year. The winter storms of 1993 can be seen to have formed a well-developed cliff at the dune base (Fig.2.11). Photogrammetric surveys are made after each severe storm surge. The present dune belt is so narrow that even one storm surge may be sufficient to initiate a break-through.

Fig.2.11. Formation of a beach cliff and erosion of the coastal dune belt by a storm surge in the autumn of 1993 (Photo: I.Heyse)

9.3. Coastal dyke damage

The most dangerous conditions for the coastal dykes are presented by westerly and north-westerly winds exceeding force 9. In 1990 alone, there were nine severe storms that caused damage to the dykes in the Ostend area assessed at 250 x 10^6 BF. The total bill for the whole coast is estimated to be an average of 300-400 x 10^6 BF per year.

9.4. Beach aggradation

About six segments of coastline are characterised by beach sedimentation, but because of longshore drift and sediment reworking they cannot be sharply demarcated from the segments where erosion is paramount. However, it is known that the harbour entrance to Blankenberge is silting up, mainly because of aeolian sand movement. The Zwin, the last area of intertidal salt marsh in a natural state in Belgium, is also showing aggradation. The harbour of the city of Bruges has been suffering from silting since historical times and is no longer in use as such. Various techniques are used to offset excess sand supply, such as artificial dredging and excavation of the sea floor near the mouth of the Zwin creek.

9.5. The Coastal Safety Plan 2000

To ensure the safety of the coastal plain, a wholly new plan was set out by the Flemish Government in 1993, named the Coastal Safety Plan 2000, analagous to the SIGMA Plan. Three lines of sea defence are proposed:

1. The first coincides with the present coast (beaches, dykes and dunes)
2. The second is situated a few kilometres inland, parallel to the first. Large parts of the present main road and the tramway line are incorporated.
3. The third coincides with the 5m contour marking the natural limit of the coastal plain.

Some supplementary dykes are to be constructed between 1 and 2 to protect the most sensitive areas.

10. Conclusion

Despite the absence in Belgium of many major hazards that elsewhere in the world provide the most serious threats to man, such as severe earthquakes, volcanoes or tsunamis, there are many lesser hazards regularly encountered - localised river flooding, subsidence, landslides and soil erosion, to mention a few. The most serious threat to national safety is undoubtedly that posed by storm surges and dyke breaching, as happened in 1953. To this end, major plans to protect the population in the future are in hand, notably the SIGMA Plan and the Coastal Safety Plan 2000, but their full implementation will need further time. Warning plans on a national basis (Civil Protection Service) and on a regional level (Provincial Protection Plans) are already in place to cope with future calamities.

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Hydrological Service, Coast Ostend: B.De Putter

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CZECHIA AND SLOVAKIA

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1. Introduction

Geomorphological hazards represent extreme events that occur as a response of the dynamic systems of the Earth to both internal and external changes. These changes are often brought about or accelerated by human activities and are well exemplified in the area of the former Czechoslovak state (for convenience, this will be referred to as Czechoslovakia, since this article was written before the division of the country in 1993). Areas in both Czechia and Slovakia, but especially the latter, are threatened by a wide array of potential hazards, including seismic disturbances, mass movements, floods, soil erosion by wind and by runoff, and subsidence.

2. Seismic hazards

Seismic shocks, varying in intensity and frequency, affect the Carpathians in Slovakia, and to a much lesser extent, the Bohemian Massif in Czechia. The most active zone forms a belt running from the Eastern Alps to the Western Carpathians (Procházková, 1984). It is characterised by a high density of earthquake foci with epicentral intensities as high as VIII on the MSK scale, concentrated along the deep-seated tectonic border between the Bohemian Massif and the Western Carpathians, the so-called Peripieninian lineament (Fig.3.1). The most frequent earthquakes have been recorded in the sector of the Malé Karpaty mountains running north-east from Bratislava and corresponding to the subduction zone where the Bohemian Massif plunges below the Carpathians. For example, in 1858, Zilina was hit by an earthquake with an epicentral intensity of VIII, affecting an area of 66 000km^2.

In the central and eastern parts of the Western Carpathians, the foci are more dispersed and do not appear to show definite lineaments, but this may be due to the low density of settlement and inexact knowledge of the location of foci in the past (Schenková, Schenk and Kárník, 1984). This area was affected by the dome-like uplift of the Pannonian region in the Tertiary, as well as by more local faulting. It is possible that the extension of earthquakes along active faults towards the periphery of the up-warp is connected with the Pannonian mantle diapir (Cech, 1988). According to Ondrásik

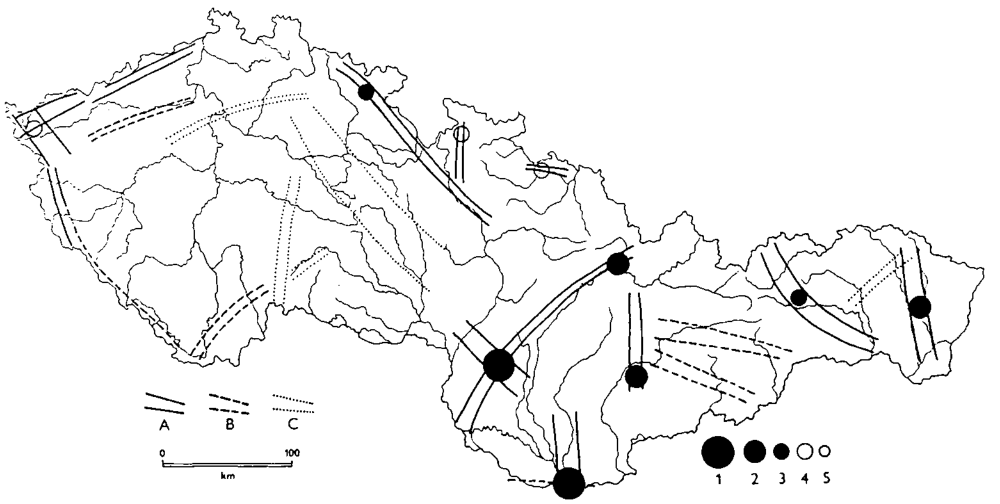

Fig.3.1. Seismic hazard regions in Czechoslovakia. The seismo-active lines marked by earthquake epicentres are classified according to Procházková (1984) as follows: A. Distinct seismo-active lines, B. Less distinct, C. Assumed. Earthquake epicentres with felt intensity (MSK scale), after Schenková, Kárník and Schenk (1984): 1. IX or more; 2. VIII; 3. VII; 4. V-VI; 5. IV-V

(1988), earthquake foci are related to differential block movements, which in turn are linked to the domal uplifts. The high mountain ridges are probably less affected by shocks than the basins which are more seismically active. In the sinking basins, strain energy accumulates, whereas in the tectonically rising massifs there is constant release of strain (Škvor and Zeman, 1976). Lower levels of seismic activity are, however, manifest in the younger ranges, for example, Vihorlat in the Eastern Carpathians. The central Slovakian seismic area, lying between Banska Stiavnica, Banska Bystrica and Lubietova is connected with north-south lineaments. In 1443 there was a devastating earthquake here with an epicentral intensity of VIII-IX.

The earthquake of 1763 in Komárno/Komarom in the Danube lowlands is considered to have been the strongest in the area of Czechoslovakia. During this shock, with an epicentral intensity of at least IX, 63 people were killed and many buildings destroyed. This relatively small seismic area lies clearly at the intersection of the so-called Raba north-south lineament with the fault system along which runs the Danube and which is linked with the so-called *Thermenlinie* of the Vienna basin (see page 27). In addition to the 1763 shock, other destructive earthquakes subsequently affected the town and its surroundings, the latest being in 1832, which significantly affected the development of the region.

The mountain arc of the Eastern Alps also causes stresses to develop in the Bohemian Massif (Procházková, 1984). The weak and relatively infrequent earthquakes of this area are transmitted along pre-existing faults: the fault network of the Bohemian Massif was largely completed by the end of the Variscan orogeny. After the consolidation of the Massif in the Mesozoic and Tertiary, there were renewed movements along these faults, extending to the present day. Earthquake foci in the Massif are associated with the ring of surrounding mountains: the Bohemian Forest, and the mountains of Smrciny, Krušné hory, the southern foot of the Lužické hory, Krkonoše, Orlické hory and Hrubý Jeseník. Among the stronger motions recorded, there was the seism of 1901 in the upper Upa valley (Krkonoše) with an epicentral intensity of VII and, in 1983, VI-VII; and the seism of 1935 in Ramzová (Hrubý Jeseník mountains), V-VI. Other important events took place in the area of Opava (1931; up to VI) and near the active Hronov-Poříč fault which caused the latest earthquake in 1979, epicentral intensity IV-V (Schenková, Schenk and Kárník, 1984). The foci of these earthquakes lay at depths of 3-18km.

Exceptional seismic phenomena in the Bohemian Massif are related to places where deep active faults intersect. This is the case in western Bohemia between Františkovy Lázně, Aš, Kraslice and Sokolov, where the deep Litoměřice fault, with the basins of the Ohře rift zone, crosses the Western Bohemian deep-fault zone marked by the Mariánské Lázně fault. In such places the crust is divided into numerous, weakly-connected blocks which move easily against one another (Procházková, 1984). Such movements show up in a succession of weak shocks (up to VI) at intervals as frequent as monthly or even daily, known as an earthquake series. The last earthquake series occurred in Western Bohemia in 1985-86, when the strongest shocks reached VI-VII. Earthquakes in Western Bohemia have been recorded since the twelfth century; during the stronger shocks, much damage was done to buildings, chimneys were destroyed, roof tiles and wall plaster were cracked or fell down and hanging objects set in motion in the area close to the epicentre. There were also explosive sounds and changes in the circulation of mineralised waters adjacent to spa areas. The effects of these earthquakes on slope stability in the Krušné hory have been evaluated because of the possible influence on the brown-coal mines at the base of the mountains: no such increase in landsliding has been found, however (Tobyas et al., 1987), nor has the mining itself been found to affect the incidence of earthquakes (Drozd-Rybář, 1983).

Weak earthquakes (less than V) with shallow foci occur sporadically in the Bohemian Massif; little is known about their patterns, and they seem to be due to the local balancing of forces in the subsiding areas.

In order to assure the safety of industrial buildings, energy installations and other structures, a series of maps has been compiled showing earthquake epicentres (Procházková and Brouček, 1979) and seismic regionalisation. Attempts have also been made to use morphostructural analysis to demarcate seismically active zones. The use of geomorphological methods to complement seismological and geological investigations has proved valuable; Demek and Kalvoda (1992) have used such techniques in an analysis of the safety of the nuclear power installations at Bohunice and Temelin.

3. Mass movements

3.1. Rockfalls

Although there are many areas of highly dissected relief, conditions favourable for rockfalls (steep slopes and free faces) are encountered in only a small part of the territory (Fig.3.2).

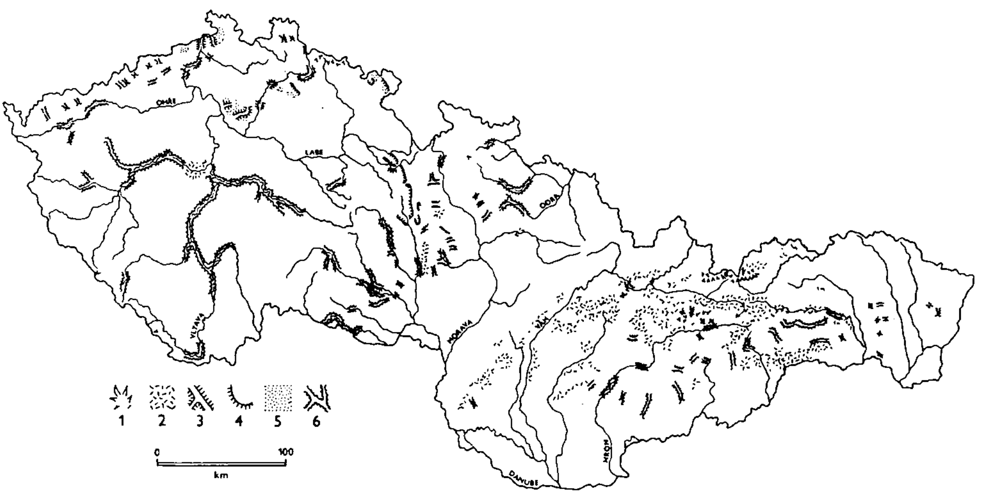

Fig.3.2. Localities subject to rockfalls (Kolejka, 1990). 1. Glacially sculptured landforms in mountain regions; 2. Rock faces in karst regions; 3. Gorges in tabular sandstones; 4. Cuesta scarps of sandstone and marlstone; 5. Castellated sandstone formations; 6. Deep valleys cut in crystalline and massive sedimentary and volcanic rocks.

Areas of steep glacial relief show the most concentrated incidence of rockfalls and associated accumulations, namely, in the crystalline high mountains (the Carpathians: High, West and Low Tatra), in some mountain areas with Mesozoic cover rocks (Belanské Tatry, West Tatra) and in the flysch mountains of the Slovenské Beskydy (Babia hora). In the Czech Highlands, there are only relatively isolated cirques and troughs in the Krkonoše and Šumava mountains where rockfall features appear.

Fallen rocks may cover quite large areas, especially in the High Tatra where individual accumulations can be as much as 400 x 600m or 850 x 200m in size (Němčok, 1982); these are mostly of prehistoric age. During the earthquake of 9 August 1662 (Špůrek, 1972), there was a major rock slide at the Lomnický štít (peak) in the High Tatra (2634m); and according to some records, the altitude of the Slavkovsky štít (2453m) was lowered by 300m at the same time. The accumulations of rock debris below the two peaks are the youngest in the High Tatra, though minor rockfalls occur every year.

Karst areas possess some steep walls associated with gorges, collapsed caverns and cliff-bounded outliers such as klippen. In the areas of the Czech and Moravian karst, there are numerous rock faces; there was a minor rockfall near Holštyn in 1885. In the more extensive karst areas of the Carpathians, there are many more forms with precipitous sides; major rockfalls have occurred from the limestone of the Malá Fatra and Velká Fatra mountains, and in the Chočské vrchy hills (Baliak and Mahr, 1986; Němčok, 1982). The largest event in recent times was the rockfall of 1921 in the Hejšovina (Table Mountains) on the Polish border.

The sedimentary rocks of the Czech Cretaceous Plateau also offer favourable conditions for rockfalls at the steep edges of tabular formations. Examples can be seen in the deep canyon-like valleys of the Elbe and Kamenice in the Děčínská vrchovina upland, the Tichá Orlice river near Choceň, and some parts of the Jizera valley (Turnov). Numerous rockfalls are typical of the castellated sandstone outcrops such as Prachovské skály, Adršpašsko-teplické skály, Broumovské stěny, Kokořínsko and Tiské stěny. Rockfalls are frequent on scarps at the edges of the Cretaceous basin at Hříva, near Česká Třebová, where falls of marlites occurred in 1853 and 1895; at Hřebeč near Moravská Třebová (marlites and sandstones); and from the scarps of mesas such as Mt Ostaš near Teplice nad Metují in eastern Bohemia and the Skalní stěna near Moravská Třebová.

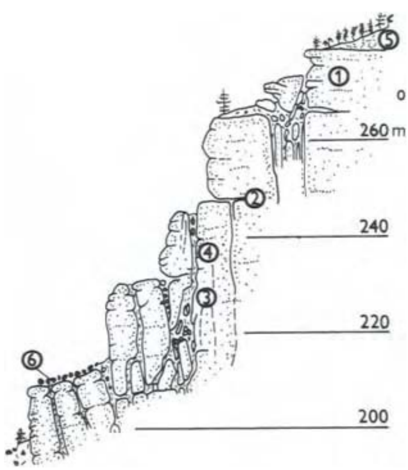

Fig.3.3. The upper edges of the Elbe gorge, consisting of deeply weathered sandstone, are liable to rockfalls (Zvelebil, 1989). 1. Turonian sandstone; 2. Lithologically-based zones of selective weathering; 3. Caves; 4. Measurement sites; 5. Sand and debris mantle; 6. Rockfall debris dating from 1978

The classic region for rockfalls is the Elbe (Labe) gorge through the Děčínská vrchovina, mentioned above. Here, falling sandstone blocks cause damage to communications as well as houses, as in 1938 (Fig.3.3). An effective monitoring system of the unstable parts of the rockwalls has been set up (Zvelebil, 1989). After a disastrous fall in 1978, protection of the Elbe traffic corridor along which trunk roads and the railway pass was recommended, and regular survey of opening fractures has been carried out (Kalvoda and Zvelebil, 1983). The data provide advance warning of about two months. A prediction which turned out to be accurate to 3 days has already been made (Zvelebil, 1984).

Rockfalls are also likely to occur along some other deeply incised valleys, from castle koppies or tors, and from frost-riven cliffs in both crystalline and massive sedimentary rocks. The rockwalls along the Vltava valley and its tributaries overhang in places, giving frequent falls (e.g. of about 1000m^3 in 1925); and there are many other instances in the Krušné hory (e.g. near Jáchymov in 1848), in the Krkonoše and elsewhere.

In the Carpathians, rockfalls are frequent in the deeply-cut valleys of the Malé Karpaty, the Low Tatra and the Slovenské rudohorie. The phenomena are most intensive on west-facing walls (Midriak, 1983).

3.2. Avalanches

The incidence of avalanches is strongly related to relief and climate (Fig.3.4). Only in a few places do the Czech Highlands reach altitudes sufficient for heavy snowfall. The natural timberline on the windward sides of steep slopes such as cirques drops below 1200m, but on gentle slopes rises to 1370m (Jeník, 1961). Localities with the most favoured conditions for avalanches occur in the Krkonoše, Králicky Sněžník and Hrubý Jeseník mountains. During settlement of the higher areas towards the end of the Middle Ages and the beginning of the modern period, the dwellings of herdsmen moved out of the cirques threatened by avalanches to the upper edges of the valleys, following numerous tragic events, for example, the disastrous avalanche of 1666 in the Obří důl valley in the Krkonoše. Deforestation of higher tracts of forest for pasture has extended the incidence of avalanches down towards 1000m, and the timberline has also been lowered owing to toxic emissions from industrial regions of Czechoslovakia, east Germany, Poland and western Europe.

In Slovakia, there is a somewhat different situation in the high mountains of the western Carpathians. Because of the narrowness of the ridges, there are only limited areas of leeward slopes for snow accumulation, except in the Velká Fatra and Low Tatra where there are areas of old flat relief on the watersheds. In the Carpathians generally, avalanches occur in the range 1000-2600m (Midriak, 1983). The contemporary timberline varies between 1250m in the Velká and Malá Fatra and 1490m in the High, Western and Belanské Tatra. Before the advent of herdsmen and miners in the Middle Ages, the natural forest limit was 200-300m higher (Kňazovický, 1967). Disastrous avalanches (and not just in exceptional conditions) can thus extend to lower elevations on pastureland. In the Moravian-Silesian Beskydy mountains, severely affected by

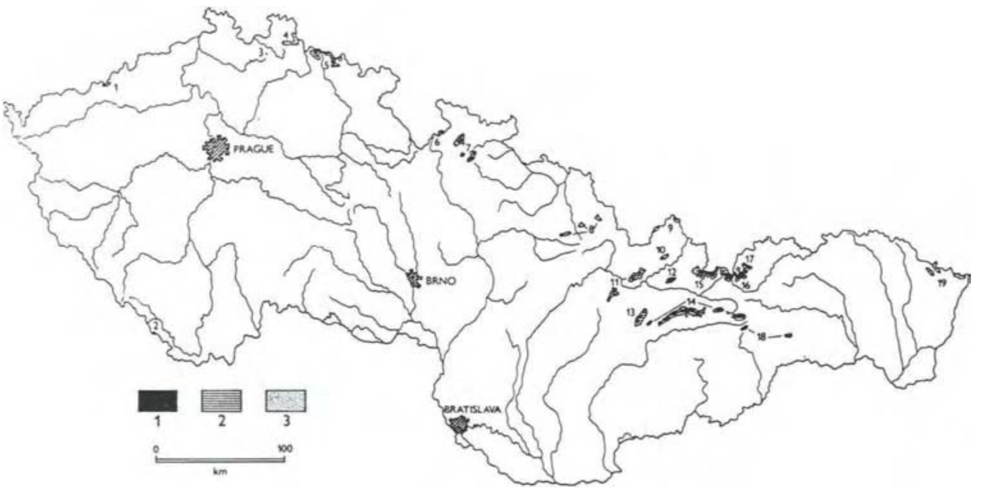

Fig.3.4. Mountain regions liable to avalanches (Kolejka, 1990). 1. Original avalanche areas above the timberline; 2. Avalanche areas above the artificially lowered timberline; 3. Forests damaged by air pollution and threatened by avalanches. Key to names of mountain groups: 1. Krušné hory (Ore Mountains); 2. Šumava (Bohemian Forest); 3. Ještědsko-kozákovský hřbet; 4. Jizerské hory; 5. Krkonoše (Giant Mountains); 6. Kralický Sněžník; 7. Hrubý Jeseník; 8. Moravskoslezké Beskydy; 9. Oravské Beskydy; 10. Oravská Magura; 11. Malá Fatra; 12. Chočské vrchy; 13. Velká Fatra; 14. Nízké Tatry (Low Tatra); 15. Západné Tatry (Western Tatra); 16. Vysoké Tatry (High Tatra); 17. Belanské Tatry; 18. Slovenské rudohorie; 19. Bukovské vrchy

industrial pollution, there are slopes extending as low as 1000m where the coniferous forest has been damaged and which are now subject to avalanches.

The avalanche hazard is thus by no means a negligible risk in the Slovakian mountains. Altogether, they affect 37 per cent of the Western Carpathians and one-fifth of all areas above the timberline - about 100km^2 (Midriak, 1983). Apart from the danger to man, there is the related loss of soil from the avalanche tracks. For example, in the spring of 1974, a wet snow avalanche on the north-west slopes of the Velká Fatra, at 1400-1500m, stripped away the humus-carbonate soil to a depth of 15-20cm over an area of 328m^2 with a slope of 32-35°, and to 25-35cm over 212m^2 with a slope of 30-32°. The total soil loss was between 0.2 and 0.39t/m^2. The eroded material was swept down to the valley. On the 21 March 1974, a channelled avalanche 500m long and 200-300m wide descended a bedrock slope of the Mengušovská dolina valley in the High Tatra; after hitting a protruding rock outcrop, it leapt across to the opposite slope where 12 people were killed.

Avalanches are most frequent in the High Tatra and it is here that most research has been done (Kňazovicky, 1967). Slopes of ≥30° are most at risk, and are usually scored by avalanche chutes which direct avalanches sometimes with volumes of over 100 000m^3. About a quarter are less than 500m^3, while 20 per cent exceed 100 000m^3. March is the most common month (55% of all occurrences), followed by February (9%), January (5%) and May (4%). They often originate in the limestone Belanské Tatry and on the southern slopes of the western Tatra denuded of dwarf pine (Červený et al., 1984).

Powder avalanches are typical of the Krkonoše and the Czech highlands. The biggest, on 8 March 1956, with a length of 1375m, slid down to the Labský důl valley; moving at high speed, the air blast in front of it destroyed areas of forest.

3.3. Landslides

Landslides are a common occurrence in Czechoslovakia: on average there is one for every 7.5km^2 (Fig.3.5). They are classified according to mechanism of movement into slides (rotational, planar and multiple), flow-type slides (flow slides, mud slides, mud flows, debris flows) and block-type failures (block slides)(Mahr, Baliak and Malgot, 1986; Němčok, Pašek and Rybář, 1974). The following landslide regions may be differentiated on the basis of controlling lithology (Fig.3.6):

1) The crystalline complex and the highly consolidated sediments of the Czech Highlands and the Western Carpathians (granites, metamorphic rocks, Palaeozoic and

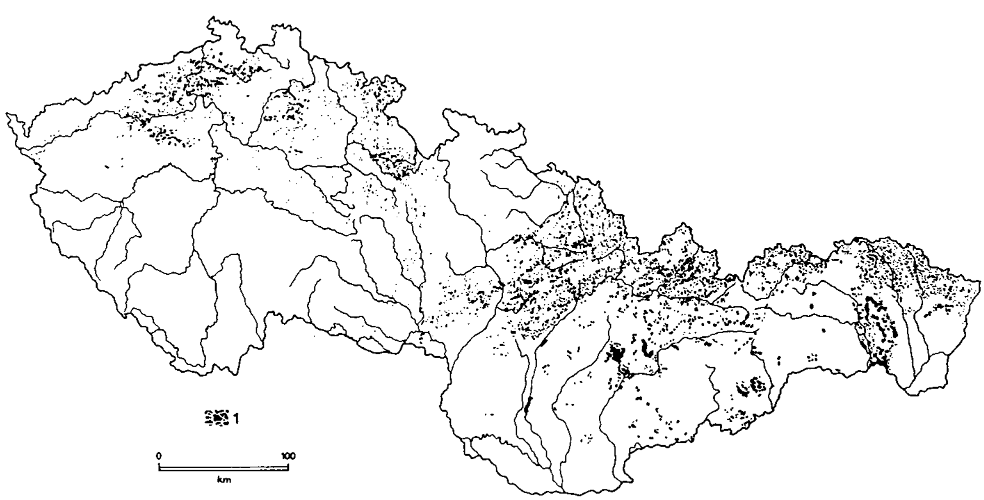

Fig.3.5. Distribution of landslides and other slope failures (after Geofond, Praha). 1. Location of slides and slope failures

Proterozoic sediments); the relief ranges from hills to mountains.
2) The Permian and Carboniferous sedimentary basins of the Czech Highlands (arkoses, conglomerates, sandstones, siltstones, mudstones); mainly hilly relief.
3) The karst regions of the Czech Highlands and the Western Carpathians.
4) The Cretaceous sedimentary plateaus of the Czech Highlands; sub-horizontal beds of sandstones, marlites, mudstones, clays and marls; the relief ranges from hills to plains.
5) The flysch zones of the Western and Eastern Carpathians with a typical irregular alternation of folded layers of sandstones, conglomerates, mudstones and marlites; hills or mountains.
6) Neovolcanic areas with extrusive and intrusive rocks, and volcano-clastites (basalts, andesites, rhyolites, tuffites and tuffs of Tertiary and, exceptionally, Pleistocene age); hills or mountains.
7) The Tertiary basins and depressions filled with both non-folded and folded unconsolidated sediments (clays, marls, sands and gravels); hills or plains.
8) Unconsolidated Quaternary deposits of aeolian (loess, sand), colluvial, fluvial (alluvium) and geochemical origin (travertine).

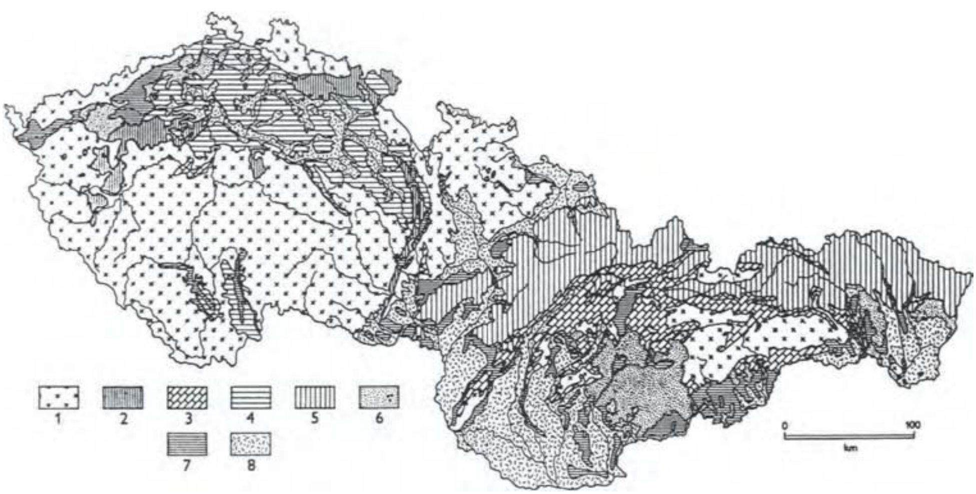

Fig.3.6. Main geological units of Czechoslovakia in terms of landslide occurrence. 1. Crystalline and old sedimentary rocks of the Bohemian massif and western Carpathians; 2. Permo-Carboniferous sediments of the Bohemian massif; 3. Karst regions of the Bohemian massif and western Carpathians; 4. The Czech Cretaceous sedimentary plateau; 5. Flysch rocks of the Carpathians; 6. Neovolcanic formations of the Bohemian massif and Carpathians; 7. Tertiary basin sediments of the Bohemian massif and Carpathians; 8. Quaternary deposits of the Bohemian massif and Carpathians

3.3.1. The landslides in region (1) occur mostly in the form of block slides where there is steep relief and the rock has been weakened by tectonics, unloading by glacial or deep fluvial erosion, or by foliation planes in the metamorphic rocks. In the Czech Highlands such failures, although rare, occur in the deep valleys of the Vltava (south of Prague), the Ohře (around Karlovy Vary) and some of their tributaries (such as the Sázava).

A locality where the risk from mass movements has been particularly investigated comprises the fault scarp of the Krušné hory (Fig.3.7), the most important escarpment of the Bohemian Massif, 700m high and 130km long. Its stability was the subject of detailed research because of the existence of the opencast brown-coal mine at its foot, and the danger that continued deep excavation here could undermine its stability. Study of the relief of the Krušné hory has shown that the fault-scarp morphology is comparatively young and that it has been subject to catastrophic mass movements in the past. Remnants of extensive block slides were discovered at the foot of the scarp near the village of Dřínov, north-east of Chomutov, where 17-20 million m^3 of debris including blocks of gneiss have come to rest on top of Miocene basin sediments (Špůrek, 1974). Since the material is also weathered, it is thought that the collapse is probably of Pleistocene age (or even older), but at the same time it seems unlikely that the processes have ceased entirely. All major joint planes, discontinuities and shear surfaces (Marek, 1984) were investigated but, apart from some superficial loosening and slow long-term creep, no evidence of features that could seriously affect the stability of the slope were found (Rybář, 1984), nor was there any sign of induced seismicity that might be related to internal movement (Drozd and Rybář, 1983).

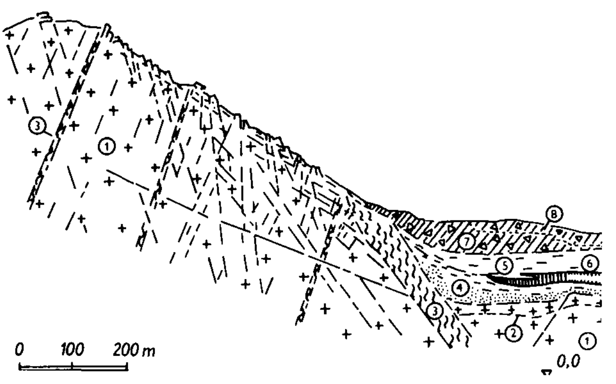

Fig.3.7. The fault scarp of the Krušné hory in the Jezerka region and its structure (after Rybář, Zika and Avramova-Tačeva, 1986). 1. Massive orthogneiss; 2. Kaolinised orthogneiss; 3. Weakened zone (tectonically crushed and locally altered rocks); 4. Miocene sedimentaries (lower part fragmented and sandy, upper part clayey); 5. Coal seams exploited in underground mining; 6. Clays; 7. Quaternary rockfall and other slope deposits; 8. Proposed safety pillar

Deformation in the crystalline rocks of the Carpathians (Němčok, 1982) is most often related to gravitational spreading of ridges, resulting in the formation of cracks and longitudinal displacements, including grabens, and gravitational folds on the high mountain slopes (Fig.3.8). These slow and deep-seated creep deformations extend down to depths of 250-300m in the rock mass (Němčok, Pašek and Rybář, 1986); rapid slides are, however, rare.

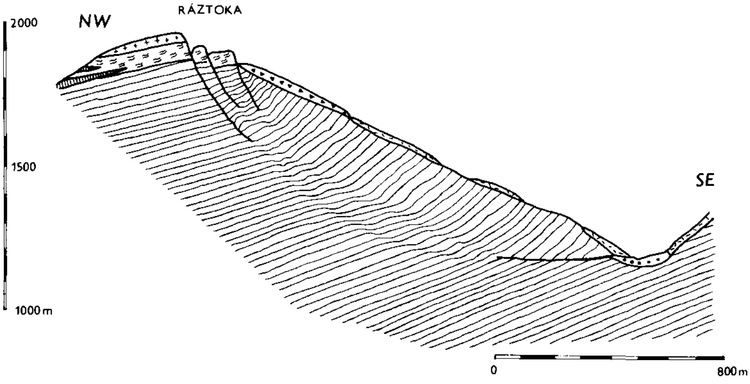

Fig.3.8. Profile across the Ráztoka ridge (after Mahr and Němčok (1977) in Němčok (1982)). 1. Quartzite paragneiss; 2. Migmatite and granitoid rocks; 3. Slope failure; 4. Rockfall and slope debris; 5. Fluvial deposits

Debris flows and slides are more frequent, up to 1km long and 10-40m wide, in the West and Low Tatra (Němčok, 1982; Baliak and Mahr, 1986), originating in areas above the timberline during heavy rainfall and extending down to the forest. For example, in the western Tatra on 19 July 1970, after rainfall totalling 215.5mm, a debris flow starting at 1350m and running down to 850m reached a length of 1km. Similar debris flows occur in the Krkonoše, Hrubý Jeseník and other mountains.

3.3.2. In landslide region (2) there are only exceptional slides where blocks of sandstone have moved over more plastic mudstones. The block slide near Mladotice in western Bohemia in 1872 caused the formation of a lake (Špůrek, 1972). More recently, a disastrous slide in the foothills of the Krkonoše near Košťálov was recorded in 1975.

3.3.3. In the karst region of the Czech Highlands (3), the landslides consist mainly of blocks moving down the surfaces of debris cones, and toppling failures in the deep and sometimes dry gorges. *In the karst of the Western Carpathians (3)*, there are slope failures along overthrust fault-planes (Němčok, 1982). Additionally, as erosion cuts through the limestone or dolomite to expose the shale basement, block slides occur, as from the mountain of Rozsutec (1610m) in the Malá Fatra (Fig.3.9). One of the largest such landslides in the Carpathians was recorded near Chleb (1646m; Baliak and Mahr, 1986).

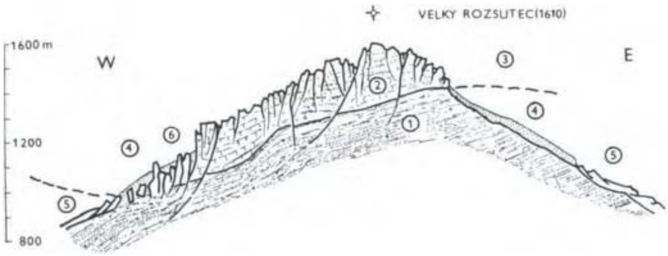

Fig.3.9. Profile across the Vélký Rozsutec ridge (after Němčok and Baliak, in Němčok (1982)). 1. Marly limestones and shales; 2. Rifted limestone and dolomite blocks (Middle Trias); 3. Overthrust; 4. Blockfield; 5. Slope debris; 6. Landslides

In the klippen zone, displacement of carbonate blocks from the parent mass takes place along softer flysch layers.

3.3.4. The region (4) of the Czech Cretaceous Plateau is characterised by slope failures associated with both horizontal and gently dipping beds. Planar slides, flow slides and rotational slips occur in the deeply weathered mantles covering the marlites and mudstones. These lithologies also act as glide planes for block slides in the overlying hard calcareous sandstones, as around Mělník. There are frequent landslides on talus slopes beneath the sandstone walls, moving over the underlying marlites. Near Dnebohy on 27 June 1926, a 30ha area of the slope started moving, down to a depth of 30m. The displacement lasted for 5 hours, involving a mass of 3 million m^3 and leaving a scar up to 5m high. Other areas of frequent block slides in this region comprise the borders of the Cretaceous Plateau where the limestones and sandstones overlie the plastic layers of Permian mudstones and clayey sandstones.

3.3.5. The flysch zone (5) of the Outer Western Carpathians and the Palaeogene basins of the Inner Western Carpathians are the most important region for landslides in Czechoslovakia. The decisive factor is the structure of the flysch, but the distribution of groundwater and the relief energy are also important. Three basic groups of landslide can be distinguished: block-type slides along bedding planes, block displacements on scarps and, most common, landslides on debris slopes. Several generations of landslides are often present, while similar mass movements also affect the flysch zone of the Eastern Carpathians (Demek et al., 1965; Menčík, 1988; Němčok, 1982; Pesl, 1987).

3.3.6. Landslides in neovolcanic areas (6). Mass movements affect the edges of the volcanic regions of the Czech Highlands and the Carpathians, where the volcanites rest on the plastic basement of Cretaceous, Palaeogene and/or Neogene deposits. The inner parts of the volcanic regions are less affected, except in the case of stratovolcanic complexes where layers of resistant lava alternate with less coherent pyroclastites or soft volcano-sediments. In the České středohoří mountains, block-type landslides in the gaps cut by the Labe and Bílina rivers are frequent; also the flow slides and planar slides of volcanite debris along the outcrop of the Cretaceous basement (Němčok, Pašek and Rybář, 1986). In 1898, part of the village of Klapý was destroyed by a landslide of basalt debris over the Cretaceous marls, which moved at 5km/hour and whose front reached a height of 8m. In 1936 there were renewed movements and the inhabitants had to be evacuated.

The southern edges of the Carpathian volcanic mountains rest on Miocene sedimentary and volcano-sedimentary formations. Tectonic fracturing and uplift of the volcanic massif led to conditions favourable to block slides, which affect up to two-thirds of the periphery of the West Carpathian volcanic ranges (Němčok, 1982). The slides dammed some lakes such as Morské oko in the Vihorlat mountains, and Izra and Malá Izra in Milíč. Recent disastrous landslides are typical of the Slovenské strědohoŕie mountains, especially the Vtáčnik mountains and the Kremnické vrchy, into which the tectonic basins extend, disturbing the margins of the volcanic rocks resting on the Tertiary clays.

The disastrous landslide near Podhradie in 1978 resulted from favourable geological and weather conditions, and also coal mining (Malgot and Mahr, 1980). Undermining caused displacement of about 24 million m^3 of material from an area of 27.4ha. Several houses, communication and technical centres were destroyed over several weeks. The largest landslide of modern times, however, occurred near Handlová, causing damage that extended over 156km^2.

3.3.7. In the Neogene basins (7), the common cause of instability is the presence of sand and gravels overlying less permeable clays or marls. Such sequences are exposed by valley incision, or in cuttings made by man. The basins in the north-west of the Czech Highlands (Cheb, Sokolov and Most), in the West Carpathians (Žiar, Zvolen and Košice) and in the hilly parts of the Danube lowland show both flow and planar slides on slopes, while along valleys, there are slides 1-3km long (exceptionally, up to 18km) (Němčok, 1982; Němčok, Pašek and Rybář, 1986). Isolated horsts such as Výhon in the Dyjsko-svratecký úval graben and the Hron hilly area in the Danube lowland are characterised by slope failures of the slide type. Man is an important factor in triggering such slides, which also occur during the mining of brown coal in the Sokolov and Most basins (Němčok, Pašek and Rybář, 1986; Rybář and Dudek, 1986).

3.3.8. Quaternary sediments (8) are also subject to slope failures. Slope failures in loess involve either the slumping of separated blocks or shallow flows. The tendency to landsliding is particularly marked in areas with deep gullies or road cuttings in thick loess (the south and central Moravian Carpathians, and the hilly parts of the Danube lowlands). Block slides at the edges of travertine domes resting on the flysch basement in basins of northern Slovakia are of greater importance. An example can be seen in the case of the Dreveník dome in the Hornád basin, disintegrating along older faults and fissures to a number of smaller blocks gliding down-slope. Some landslides in Quaternary deposits are the result of lateral river undercutting in non-canalised sections (e.g. the Morava river at Hodonín, the Svratka below Židlochovice, the Hron and the Nitra), and by wave action on reservoirs undercutting their banks (e.g. Nechranice).

The landslide hazard in Czechoslovakia is currently receiving much attention. Using the latest geological, geophysical, geomorphological and photogrammetric techniques in selected areas (the Most, Sokolov and Hornonitrianská basins), regular monitoring of the most threatened areas is being undertaken. Altogether, about 2 per cent of the area of Czechoslovakia is at risk, and about 600km of communication lines. In nine of the districts of the Czech Republic (Kirchner, 1990), landslides are judged to be a serious impediment to economic development. A landslide data bank has been set up in the Geofond of the Czech Geological Office.

4. Eolian hazards

Czechoslovakia is the area in Central Europe most under threat from eolian hazards. In most parts, the air circulation has a strong westerly component (Fig.3.10) which is combined with other local winds. Gales and whirlwinds are a feature of every season, but are most frequent in summer, and are usually associated with the passage of fronts. Such violent winds only last from a few minutes to an hour or so, but cause serious damage every year to forests, crops, buildings and industrial installations. Among the areas frequently subject to winds in excess of Beaufort 5 (> 8m/s) are the bottlenecks between the mountain systems, such as the Moravian Gate between the Bohemian highlands and the Western Carpathians, the Napajedla Gate between the Central Moravian and Slovak-Moravian Carpathians, the Devin Gate between the Lesser Carpathians and the Hainburg uplands, the Vestonice Gate between the Central and South Moravian Carpathians, the eastern Slovakian lowlands between the Western and Eastern Carpathians, and also a number of other valleys such as the Jihlava, and various mountain cols. The most common direction of air movement is from the north or west.

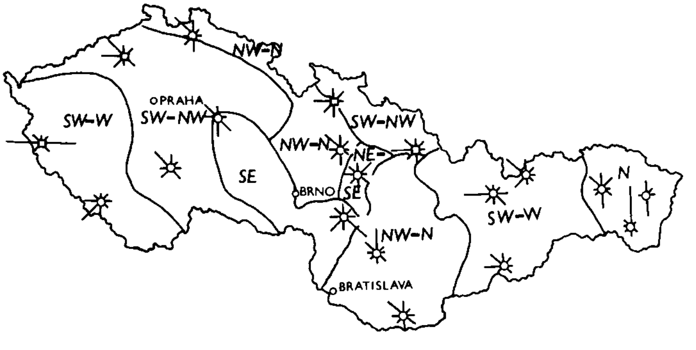

Fig.3.10. Prevailing mean annual wind directions

In some regions, local winds play an important role. Föhn winds blow primarily in winter and spring, and are known for their warming and dehydrating effects. They last on average 2 days, exceptionally up to 6 days, and the intensity can reach Beaufort 6 or more. The Föhn is most often encountered on the western slopes of the White Carpathians and causes dust storms. The Bora has different characteristics: it is a dry cold wind blowing strongly along some mountain valleys, as in the High Tatra of Slovakia.

Maximum wind speeds can attain 18km/hour. Stronger gusts are possible but rare. In 1954 a wind speed of 54m/s (196km/hour) was recorded on Lomnický štít in the High Tatra, and 69m/s (248km/hour) in 1949 at Skalnaté Pleso, also in the High Tatra.

The primary threat from high winds is deflation acting on the finer soil particles. Surface abrasion is a minor process, and deposition of wind-blown particles in leeward localities does not normally present a significant problem, though existing soils are thereby buried. All types of soil, but especially soils of light and intermediate texture, may be affected. Damage is to the top soil horizon, which lowers soil fertility, reduces humus content and removes fines. During dust storms, visibility is reduced and even breathing may be difficult, causing some health problems. In winter, alternation of dust storms with snow storms blackens the snow and leaves alternate layers of soil and drifted snow. In the lee of obstacles, windblown accumulations can attain depths of 2-3m. In the area of wind-blown sand in the Melnik and Pardubice basins, the Bor lowlands, the Dyjsko-Svratecký and Dolnomoravský úval grabens and the eastern Slovakian lowlands, even sand dunes have developed; until recently these were active, but they have now been stabilised, with great difficulty, by tree planting.

Approximately 30 per cent of the agricultural soil in Czechoslovakia is threatened by wind erosion (Fig.3.11), of which 26 per cent is in Bohemia, 45 per cent in Moravia and

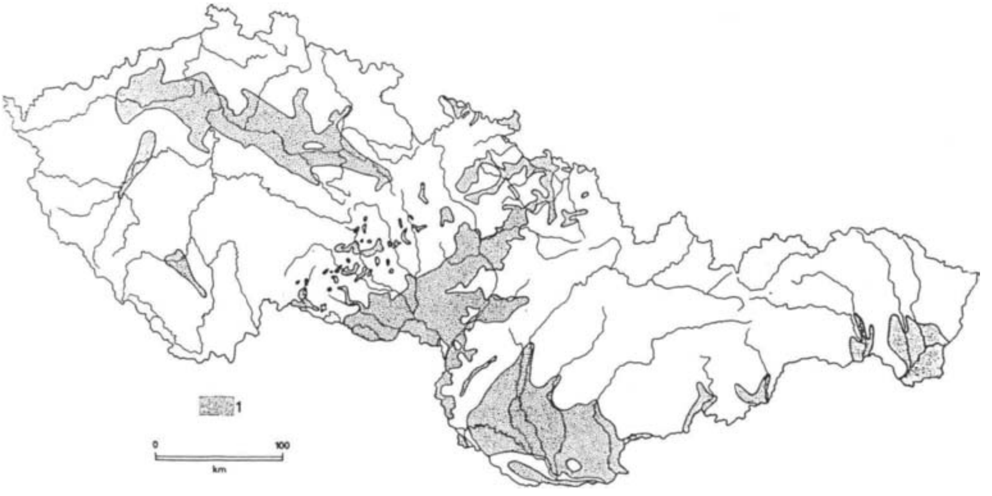

Fig.3.11. Areas subject to wind erosion

24 per cent in Slovakia, unfortunately mostly in the fertile areas. A major factor in promoting the incidence of wind erosion has been the farming systems, whereby fields have been amalgamated on cooperative farms into larger and larger units, sometimes covering 1000 or 2000ha or more, with no windbreaks.

The intensity of wind erosion varies both spatially and temporally (Zachar, 1970). During the period 1957-1989, an area in south-east Moravia in the White Carpathians was carefully monitored. In this 33-year period, there were only 3 years when wind erosion was not reported at all. Otherwise, there were 5 years characterised by weak erosion, 6 years with intermediate erosion, 9 years with strong erosion, 9 years with very strong erosion, and, in 1972, catastrophic erosion was recorded in the Bánov area. Here, in a field of 33ha, 6700m^3 of soil were removed, a rate of 203m^3/ha, and the winter wheat crop was destroyed. The average yearly intensity was 37.8m^3/ha, equivalent to a layer 3.78mm in thickness and on Zachar's (1970) scale of erosion, corresponding to "strong erosion". Figure 3.12 shows the annual fluctuations in intensity, which are typical of all areas of Czechoslovakia subject to wind erosion.

Until now, the Bánov catastrophe has been the most severe wind erosion event in Czechoslovakia, but many other examples of serious erosion have occurred. In 1926, in Veselí n. Moravou, soil was blown over the railway which was blocked for several

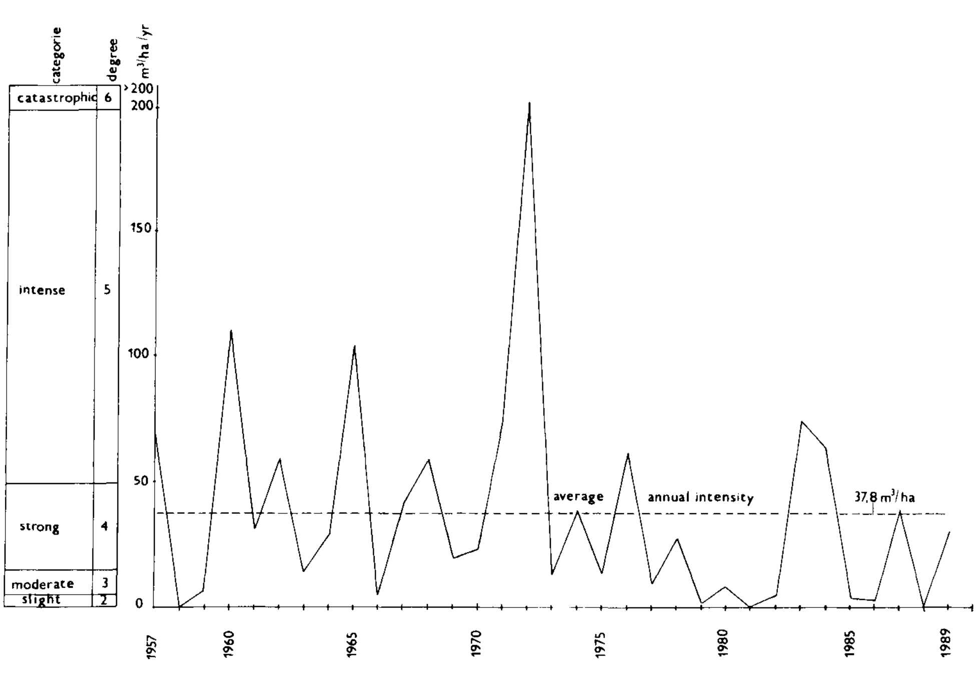

Fig.3.12. Graph showing variation in intensity of wind erosion in the period 1957-1989 in Bánov, Bílé Karpaty (Švehlík, 1990)

kilometres. In 1957, drifting soil in the Bánov area covered the main road for 400m, forcing its complete closure. In 1965, during a dust storm in the south Moravian district of Breclav, 600ha of sugar beet and tobacco, and 36ha of cucumbers were destroyed. The effects of the damage can be seen overall in lowered agricultural production. Wheat losses in southern Moravia, for example, amount to hundreds of tonnes annually. At the same time, there is loss of important minerals from the soil. In 1976, the following losses were measured from a 2396ha field at the cooperative farm in Polesovice: phosphorus 8.2t, potassium 19.6t and magnesium 5.3t. Reimbursement provided by state insurance reached 5.92 million Kčs (Czech crowns) for south Moravia in the period 1957-1974 - an average of nearly 1000 Kčs per hectare each year. The actual loss of agricultural production attributable to wind erosion can be up to 4600 Kčs/ha/year.

5. Soil erosion by water

Under natural conditions in central Europe, runoff was limited by a coherent vegetation cover. Such conditions existed until man began to settle and cultivate the land. Gradually, deforestation and destruction of the vegetative cover brought about accelerated runoff, followed by erosion and floods. Once such processes had started, the adverse effects of other factors became important - the degree of dissection of the landscape, slope angles, precipitation characteristics, the effects of lithology and soil characteristics, especially coherence and permeability, and so on. There is much historical evidence concerning accelerated erosion, first in the oldest-settled lowlands, then the adjoining hilly areas and eventually the Bohemian Highlands and Western Carpathians.

5.1. Gully and rill erosion

Gully erosion is one of the most significant signs of accelerated erosion. Conditions favourable for gullying are widespread in Czechoslovakia, while gully density varies with local conditions, mostly depending on the rock resistance. Regions most liable to gully formation include those with deeply weathered bedrock or rocks lacking cohesion such as loess, tuff, sands, etc. Generally, too, the incidence and density of gullying increase eastwards. While gully density exceeding 1km/km^2 is relatively rare in the Bohemian Highlands, values in excess of 4km/km^2 are found in the Western Carpathians, and over 10km/km^2 in the loessic loams at the foot of the Eastern Carpathian volcanic ranges. In the dissected relief of the Western and Eastern Carpathians of Slovakia, gullied surfaces extend over some 16 500ha, with a total length of 16 400km and an average width of 10m: the area is about 0.3 per cent of Slovakia (Zachar, 1970). The most developed gully systems are to be found in the zone at the foot of the mountains, along the contact with the Quaternary and Neogene cohesionless basin sediments (Bučko, 1982).

In Moravia, in the area between the Bohemian Highlands and the Western Carpathians, the gully network attains a density of more than 250m/km^2 over an area of

5513km^2, or about one-fifth of the area of Moravia (Švehlík, 1984). Locally, densities rise to 3km/km^2, especially in the loess regions of southern Moravia and in the flysch mountains (Buzek, 1984).

In the Bohemian Highlands, gully systems are present in the border mountains, in hilly areas and on the slopes of deep valleys. The upper part of the Berounka river basin in western Bohemia is an example of an area with closely-spaced gullies. In the area around Rakovník, underlain by Precambrian shales and Permo-Carboniferous sandstones, gully density approaches 1.2km/km^2. The system is supposed to have developed over the last 250 years, triggered by destruction of the road built on weathered sandstones in the catchment of the Rakovnický potok (brook)(Zachar, 1970). On average, about 65m^3 were removed each year from gullies extending over an area of 954ha. Data were obtained from comparison of old maps from the 18th and 19th centuries and other archives. Figure 3.13 shows the growth of gullies between 1825 and 1877 around Ivančice; land here was also affected by sheet erosion over some 40ha (Láznička, 1957). Analysis of documents in the Archives of the South Moravian Region has revealed that 380ha had to be taken out of agricultural use because of erosion in three of the former districts between 1785 and 1820.

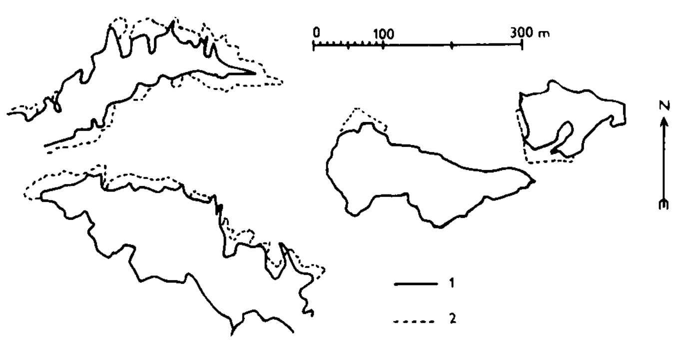

Fig.3.13. Growth of gullies in the vicinity of Ivančice in the period 1825-1877 according to old land surveys (Láznička, 1957). 1. Margins of gullies in 1825; 2. Margins of gullies in 1877

5.2. Causes and rates of accelerated erosion

In the Carpathians, it has been shown that intensive pastoralism causing soil degradation and accelerated erosion (including sheet erosion) has resulted in the removal of 30cm of soil during the past 200 years (Zachar, 1970). About 2 per cent of the agricultural land in Bohemia and as much as 10 per cent in Slovakia are estimated to have been degraded by erosion in the late 1880s. The main causes of accelerated erosion can be attributed to deforestation for fields and pasture, changes in the cultivation systems, more intense land utilisation and increasing road density. After a period of unrestrained deforestation, erosion control measures and gradual reafforestation of areas threatened by gully erosion have been introduced this century.

In 1985, the extent of agricultural land in Czechoslovakia was 68 900km^2, including 47 800km^2 of arable land. This is out of total area for Czechoslovakia of 128 000km^2. About 46.5 per cent of the agricultural land is believed to be threatened by soil erosion at present (Buzek, 1985). Since 1945, other adverse trends and practices have affected the agricultural landscape:

- intensification of agricultural production with 2- to 10-fold increases and, locally, up to 100-fold (Bulíček et al., 1977);
- amalgamation of farms and fields under collective ownership, and a transition to large-scale production;
- increases in the areas devoted to erosion-inducing crops such as potatoes and maize;
- removal of earlier attempts at erosion prevention (grass strips, etc.) and increases in slope lengths;
- inadequate measures to protect the soil on cultivated slopes in excess of 30°, partly due to lack of proper technical equipment;
- soil compaction;
- the inclusion of regions of densely-spaced dells (up to 3.7km/km^2) in large-scale production units (Hrádek, 1989).

The processes of accelerated erosion are set in motion by rapid snowmelt combined with rainfall, or by intense convective rainstorms in spring or summer. The most dangerous are spring storms, especially in April when the soil is not yet protected by crops. At such times, the slopes of dells and dry valleys can be rapidly eroded, sheet erosion on the upper parts passing into rills and a fan-like system of gullies up to 1.5m deep lower down (Hrádek, 1989).

In the less consolidated sediments of the Carpathian Foredeep in Moravia, gullies

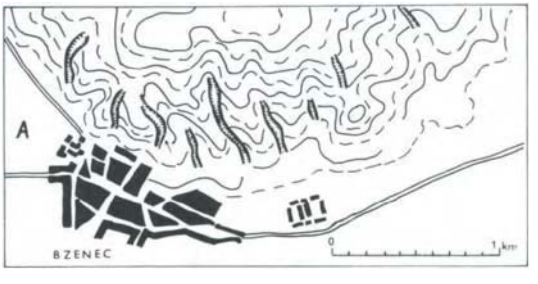

Fig.3.14.A: Gully systems north of Bzenec (southern Moravia), threatening the town with floods and mudflows, as in June 1953 (Stehlík, 1954).

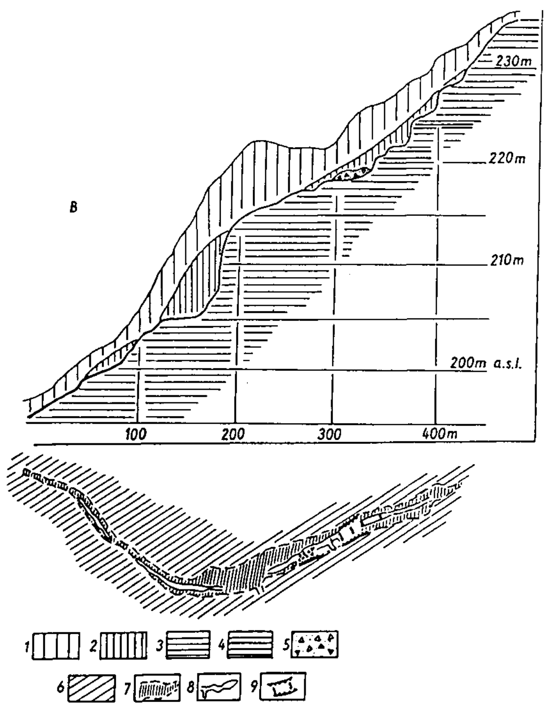

Fig.3.14.B: Long profile of one of the gullies in Fig.3.14.A (arrowed) and its plan form (Stehlík, 1954). 1. Long profile of the old road cut; 2. Long profile of the new gully; 3. Unconsolidated Pliocene sands, susceptible to erosion; 4. More resistant Pliocene clays; 5. Debris from collapsing sides, damming the bottom of the gully; 6. Original surface; 7. Plan of the old road cut; 8. Plan of the new gully with piping in its walls; 9. Gully walls subject to collapse, and steps in the gully floor

form more rapidly. In an area of Pannonian sands south of Bzenec in early June 1953 (Fig.3.14 A and B), there was heavy rainfall of 77mm in 3 hours. Rills up to 50cm deep formed on the slopes of vineyards (up to 20°). Torrents of water cut gullies 7-8m deep along footpaths; soil washed down from tracks and vineyards covered the square and streets of the town with a layer up to 100cm thick (Stehlík, 1954). In cohesionless sediments, gullies form rapidly but also quickly fill in as the sides collapse, becoming overgrown and stable, but in loess, gullies keep their vertical sides.

Intensive soil removal by sheet erosion has occurred in the loess regions of southern Moravia. In the basin of the Starovický potok (374ha), fine-grained deposits covering 13.8ha of the floodplain and with a volume of 304 755m^3 have been discovered (Mařan, 1958). It took 48 years for this material to accumulate, during which time the average annual rate of soil removal must have been 17.6m^3/ha. According to Zachar (1970), this is the highest intensity of long-term erosion so far recorded in Czechoslovakia.

In the foothills of the Low Tatra, rapid and intensive erosion has been found in several localities. In one case, a gully system 677m long and up to 1m deep formed on a 16° slope following two heavy rainstorms (42.5mm and 46.9mm respectively) in early July 1954 (Zachar, 1970). The gullies originated because areas of pasture and a road which concentrated the runoff were located on the slope higher up. Such events are quite frequent in the Western Carpathians and demonstrate the adverse effects that both roads and grassed areas can have on runoff. Zachar (1970) quotes another example from the carbonate mountains. As well as heavy rainfall, deep erosion was caused by cultivation of potatoes (which provide only limited ground cover) in furrows running downslope (angle up to 20°). Table 3.1 gives some more detail on this event, and also shows that on a neighbouring field planted with rye, erosion was much less.

Table 3.1. Data on rill erosion on potato and rye fields at a site in the Carpathians

Distance from upper edge of field (m)	Slope angle (degrees)	Potatoes		Rye	
		Soil removal (m^3/ha)	Percent of area damaged	Soil removal (m^3/ha)	Percent of area damaged
10	10	209.00	26.3	-	-
20	15	255.85	26.0	-	-
30	20	282.85	33.9	12.77	3.8
40	18	318.15	31.9	17.08	5.6
50	16	329.53	30.2	9.69	4.3
60	12	193.54	19.1	3.08	1.5
70	10	62.15	15.8	-	-
	Means:	235.87	26.5	10.65	3.8

Again, where pasture land was situated above potato fields, the soil and the plants were completely destroyed. The soil removal in this example is estimated at 1.1m^3/ha. Similar extreme cases were also found in the Bohemian Highlands on the slopes of the Nízký Jeseník mountains (Demek and Seichterová, 1962; Czudek, 1962) after rainfall amounting to over 30mm. Rill erosion was evident on a slope of just 2°. After a storm of 24-36mm, more than 1000m^3 of soil were removed from 1ha.

Rainfall intensities of 0.2 to 0.5mm/minute combined with a total fall of 5-15mm have been regarded as critical in terms of erosion, depending on the character and angle of the slope (Zachar, 1970). The intensity of erosion can be evaluated by measuring the load carried in suspension or on the bed of the stream draining the area.

5.3. Effects of deforestation and forest damage

Erosion rates are also strongly affected by the vegetative or crop cover, and especially the forest cover. In Czechoslovakia, the forest has been severely damaged by toxic emissions from power stations and industry: 70 per cent of the forest is damaged, a level that places Czechoslovakia in the forefront of all European countries. The weakened forest stands are further impaired by gales, diseases and intensive forest exploitation, particularly in the mountains; monoculture planting (dominantly spruce) also has disadvantages. The total area of forest is about 45 840km^2. Annually, some 4 million t of soil are transported as suspended load from the country, and a high proportion of this represents removal from forested areas, especially those along the northern border with Poland (the Jizerské hory, Krkonoše and Hrubý Jeseník mountains) where forests are both damaged and intensively exploited. At the same time, the mountains are subject to orographic rainfall with occasional high intensities as well as high long-term amounts. Continued deforestation using heavy machinery will lead to yet more erosion on steep slopes of unstable debris. Advanced gully erosion on some steep mountain slopes has been seen in recent years. In the late spring of 1921, the Hučivá Desná river basin in the Hrubý Jeseník mountains was deluged by 5 hours of rainfall amounting to 36mm per hour. Gullies were incised to depths of 4-6m, with widths of 10m and lengths of 500m on weathered granite slopes (Zachar, 1970).

In the Moravskoslezské Beskydy flysch mountains, soil removal from forest land reaches over 4mm a year. Table 3.2 shows the amounts of suspended load yielded by one catchment in a 6-day period. In this time, severe runoff transported as much as 40 per cent of the total load in the preceding 5 years.

Table 3.2. Soil removal during spring melt combined with heavy rainfall in the Ostravice river basin at Staré Hamry (73km^2), 9-14 March 1981 (Buzek, 1985)

Date	Snowmelt and precipitation (mm)	Average runoff (m^3/s)	Total suspended load (t)	Specific soil loss (kg/ha)
9.3	15.2	2.26	63.4	8.7
10.3	17.4	15.00	1019.6	139.7
11.3	28.0	27.70	5405.9	740.9
12.3	10.4	35.50	4899.5	671.5
13.3	1.2	15.00	1207.7	165.5
14.3	1.0	9.30	147.9	20.3
Totals:	73.2		12 744.6	1746.6

The effects of forest exploitation on runoff, soil removal and increased erosion have been investigated at experimental sites. Following a decrease in biomass by deforestation of one-third, annual runoff increased by 22 per cent. This also causes an increase in bed-load in river channels which in turn leads to the raising of channel floor levels and a greater risk of flooding. Reservoirs, ditches and canals also become silted: for example, there are now 200 000m^3 of deposits in the feeder canal for the Ládce hydro-electric station.

Part of the increase in sediment transport from areas of forest exploitation comes from the damage resulting from cutting, logging and logging tracks. Suspended load in monitored basins varied from 12.4 to 338.2t/km^2 before exploitation (Jařabáč et al., 1979; Buzek, 1979), but after construction of forest roads it increased up to three times. On average, each year, soil removal from monitored basins amounted to 33m^3/km^2, of which three-quarters came from forest roads inadequately protected against erosion. Table 3.3 shows some comparative data.

In Czechoslovakia on average, rivers transport up to 50m^3 of material from 1km^2 per year; in the dissected relief of the Carpathians, the figures range from 10 to 100m^3. Such high sediment transport clogs reservoirs with up to 1.7 million t per year, and the useful life of some reservoirs in southern Moravia has been estimated at only 60-80 years.

Soil erosion also goes on above the timberline if the turf cover has been damaged by overgrazing, burning of the dwarf pine, wear and tear due to hikers, or some natural processes such as nivation or mudflow. Midriak (1983) quotes the following rates in the high mountains: 0.1 to 0.72mm in the Western Carpathians, 0.64mm in carbonate mountains (Choč) and 0.27mm in the crystalline mountains (High Tatra).

5.4. Soil erosion: conclusion

The damage caused by all forms of soil erosion in Czechoslovakia is estimated to amount to 2000-2500 million Kčs per year. Figure 3.15 shows how widespread is the

Table 3.3. Concentration of suspended load in a stream draining from a damaged forest road compared with suspended load in a normal stream in the same area, Moravskoslezské Beskydy mountains (Buzek, 1981)

Day of sampling	Suspended load from the forest road (g/l)	Nytrová mountain creek (g/l)	Precipitation (mm)
29.4.1979	2.58	0.03	37.0
22.5.1979	1.58	0.70	39.0
12.6.1979	3.46	0.20	21.2
17.6.1979	1.45	0.05	24.4
26.6.1979	7.81	0.07	14.8

damage inflicted by intense to catastrophic erosion, reaching as much as $200m^3$/ha/year of soil loss. It is true to say that rapid erosion can occur at any time. Despite this, some regular trends in the occurrence of erosion-inducing rainstorms can be discerned: long-term observations suggest periodicity of the order of 15-20 years (Kotrnec, 1986). Spatial patterns also show that certain districts are more prone to disastrous occurrences, arising from physiographic and geological factors, and from human impact on the landscape.

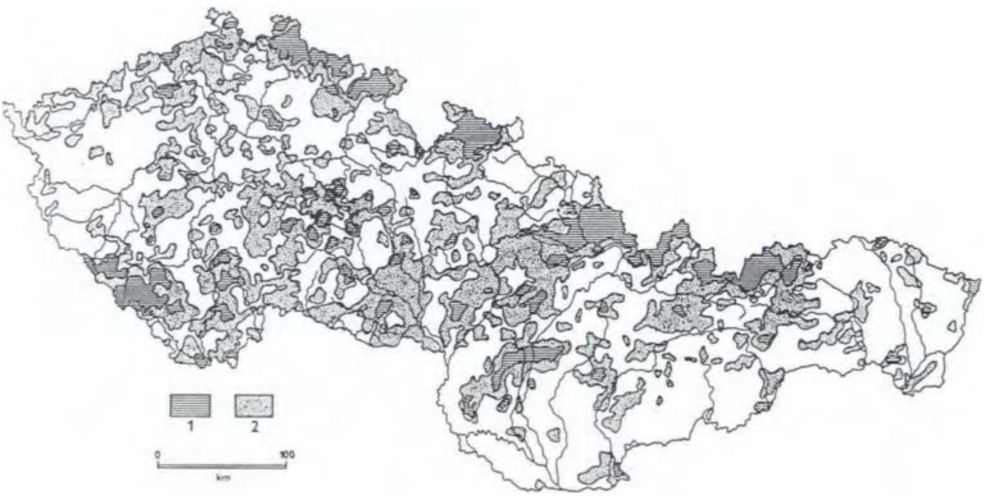

Fig.3.15. Areas repeatedly subjected to intense to catastrophic soil erosion (Kotrnec, 1990). 1. Areas most frequently subjected to catastrophic erosion (more than $200m^3$/ha/year); 2. Areas most frequently subjected to intense erosion (more than $50m^3$/ha/year)

6. Floods

Early records of floods in Czechoslovakia are to be found in chronicles dating from the eighth century, as well as in archeological evidence of buildings buried beneath fluvial sediments. Oxbows near the defensive mounds of the great Moravian princes contain deposits up to 5m thick, and archeological dating shows that 2m of these sediments were deposited from the sixth to the late ninth centuries (Stehlík, 1981). Deforestation and mediaeval colonisation of the upland plateaus were probably responsible for the devastating floods that destroyed many settlements in deep valleys and caused their abandonment. The floods perhaps also caused the demise of the early princedoms and mediaeval rulers. Remnants of thirteenth-century settlements have been discovered under thick flood deposits. The disastrous flood of 1272 severely damaged the Old Town in Prague destroying, among other structures, the so-called Judy stone bridge. After this flood, the banks of the Vltava began to be raised.

Most Czechoslovak rivers suffer from floods most often in the snow-melt period, generally from December to April. These winter and spring floods usually result from a combination of snow melting and precipitation: usually, flood waves that include snow melt reach the greatest volumes. Their hydrographs are characterised by a flat peak and longer duration than rain-fed events, and are typical of the lowland and hilly parts of the Elbe, Vltava, Morava and Danube catchments (Červený et al., 1984).

Summer floods result from regional rainfall lasting about 10-72 hours. The rainfall can be intensified and prolonged by orographic effects. Such floods usually have a smaller volume than those of the spring; the flood wave is more abrupt and may even have two or three peaks. Major floods as a rule are preceded by a subsidiary wave that represents the precipitation that first saturates the catchment. Recently, prolonged summer rainfall has caused several events that have exceeded the 100-year flood, such as in the Bodrog basin of the eastern Slovakian lowland, or in the Vltava and Berounka catchments (Červený et al., 1984).

The third type of flood is that caused by intense short-duration summer rainfall. The flood wave in this case is abrupt and short, and the volume of discharge correspondingly less than in the other types. The intensity of the rainfall can exceed 44mm/hour, and the flood peak occurs within hours of the rainfall peak. Such floods and the associated rainfall tend to affect small areas, perhaps less than $100km^2$, but can also affect belts of country including small to medium-sized catchments (Červený et al., 1984). Flash floods are characteristic of small, short streams following heavy summer thunderstorms between April and September. They can be particularly dangerous, partly because they often occur during the late evening or at night.

All three types of flood are experienced in Bohemia, a province drained centripetally by the Vltava and the Elbe. Winter and spring floods are often reinforced by ice jams. On the Vltava, floods can threaten the capital Prague: between 819 and 1954, fifty-six serious floods were recorded on the Vltava, many of which caused damage in the city. The strongest appears to have been that of February 1782, when the maximum discharge in Prague is estimated to have reached $4580m^3/s$. Since then, construction of the series of dams on the Vltava has reduced the flood danger; on the other hand, its tributary the Berounka lacks such a flood-control system. The flood of May 1872, for instance, which reached Prague, originated on the upper Berounka; it arose after a heavy cloudburst and broke through dykes, destroying a railway and killing about 50 people.

The northern part of Bohemia, especially the Jizerské hory mountains, is characterised by summer floods linked to depressions and orographically-intensified rainfall. Disastrous effects followed the flood of 1916 on the Bílá Deštná river when a dam broke. In the Krkonoše, orographic rainfall and summer snow-melt combine (Červený et al., 1984).

Flash floods are a particular risk in the corridor between the Krušné hory and the České středohoří mountains. Cold fronts passing through this route with a funnel-like effect can trigger repeated thunderstorms, as in 1927, 1979 and 1987. Precipitation in an individual storm can reach 200mm, for example in the Jílovký potok catchment and its neighbours. The last serious flood was on 1 July 1987. The dam of a small reservoir was broken, 220 houses and industrial buildings were deluged and choked with mud, and 32 bridges were destroyed (Chamas and Kakos, 1988). A flash flood on the Stěnava and the upper Metuje in June 1976 also had disastrous effects: heavy rain (100-150mm in 24 hours) caused discharge in a small catchment (157km^2) to rise to 170m^3/s, which corresponds to the 500-year flood.

In Moravia, which is mostly drained by the Morava to the Danube or by the Odra (Oder) to the north, there are spring floods related to snow-melt in the Czech highlands and summer floods related to prolonged orographic rainfall in the Hrubý Jeseník and Moravskoslezské Beskydy mountains. High levels of suspended and bed load in rivers coming from the flysch mountains of the Western Carpathians cause silting problems in the south Moravian rivers, decreasing channel capacity; channels also become blocked with vegetation owing to excessive use of nitrate fertilisers. Frequent floods on the Dyje led to construction of a system of reservoirs and dykes, but the former are now suffering from rapid silt deposition. On the Morava, too, sudden floods can follow heavy rain. In April 1988, a flash flood struck Luka nad Jihlavou at the mouth of a small funnel-like catchment (20km^2) characterised by large fields with little crop cover at the time and a dense network of dells. Over the space of 3 hours, 100mm of rain fell, leading to a flood wave that destroyed 100 houses and caused two deaths; a defective land drainage system also contributed to the disaster.

Such a disaster as this, however, is minor in comparison with the devastation caused by floods in Slovakia, which belongs mostly to the Danube basin. On the Danube itself, early summer floods are the rule. The highest discharge recorded in recent years was in June 1954, amounting to 10 400m^3/s. During a flood in 1965, there was huge damage when a river dyke near Čičov was breached and more than 400km^2 of lowland were submerged; the costs of this catastrophe totalled about 3500 million Kčs. The flood was exacerbated by a high water-table at the time. Some earlier floods have been influenced also by ice jams (for example, 1947). The Danube's largest tributary in Slovakia, the Váh, also suffers from early summer floods, which are now partly controlled by a series of dams. As in Moravia, these are suffering from silting by the high suspended and bed loads coming from flysch areas.

In eastern Slovakia there may be floods in both summer and winter, caused respectively by heavy orographic rainfall and rainfall accompanying winter thaw. The close spacing of tributary confluences along the Bodrog aggravates the flood hazard by causing water to back-up from one to the other. Floods in the Bodrog basin can affect up to 1000km^2, with extensive damage to agriculture and crops. Disastrous floods in 1712, 1813 and 1817, also affecting the Tisa, led to flood mitigation measures, such as the building of relief channels, protective dykes and pumping stations. Another related problem was the tendency of channels to shift laterally during floods, as in the 1km section near Laborec (Fig.3.16) where the displacement amounted to up to 40m annually (Pašek, 1958). After these flood reduction and channel straightening measures, peak discharges increased and a second stage was put in hand, comprising construction

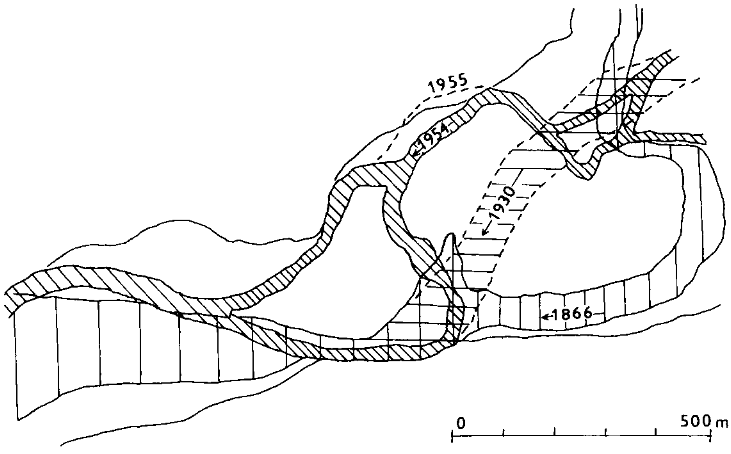

Fig.3.16. Lateral shifting of the Latorica river channel in the eastern Slovakian lowland during floods (Pašek, 1958)

of reservoirs, polders, further channel improvements and more pumping stations. Even these measures were barely adequate to control the flood of July 1980, and the state embarked on the setting-up of an automatic flood warning system.

The damage caused by floods in Czechoslovakia, averaged over the years, amounts to about 500 million Kčs per year. As a result of the damage done to ecosystems and other detrimental landscape changes by man, the situation today is that similar amounts of damage are now being caused by more frequent but smaller floods, as were caused by larger, rarer floods in the past (Červený et al., 1984).

7. Rapid subsidence

Two processes are responsible for this phenomenon in Czechoslovakia, namely, underground mining and suffosion (piping). The first of these hazards is concentrated in the Ostrava-Karviná mining district of Upper Silesia, where Upper Carboniferous coal-bearing sediments are overlain by Neogene and Quaternary deposits (fluvial, glacial and eolian). The risk of subsidence is highest where the coal mining is at shallow depths; here, the typical signs in the landscape are widened joints, steps in the fields, and especially damage to buildings, roads, railways and pipelines. In the past there have been cases of buildings collapsing. On slopes, subsidence can also provoke landslides in incoherent Quaternary materials; on lowlands, there may be waterlogging and swamp formation, and ponds up to 12m deep can form. Measured rates of subsidence can be as high as 80cm/year. Reclamation of areas where sinking has ceased is being carried out by infilling (e.g. with colliery waste), stabilisation and recultivation.

Subsidence by piping is fairly rare in Czechoslovakia, and even then most examples take place at a slow rate and do not present a significant hazard (as in the calcareous sandstones of the Czech plateau, calcareous flysch in the Carpathians, loess or unsorted fluvial sediments). An example of more rapid and hazardous subsidence by piping occurred in 1970 at the base of the Středomoravské Carpathians, where the foothills are formed of Pannonian sands and clays. During a cloudburst, there was intensive piping and penetration of water into an underground mine where 34 miners died. In the fields above, craters several metres in width formed.

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DENMARK

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1. Introduction

The great majority of hazards in Denmark result from coastal erosion and flooding in regions next to the sea, but sand storms and drifting sand can also at times present a threat. Fresh-water flooding only occurs occasionally.

The surface of Denmark is dominated by glacifluvial deposits, easily eroded by waves and currents, but owing to promontories the mainly sandy shorelines are relatively stable (Møller, 1984). However, because of its sandy coasts and low heights above sea level, large parts of Denmark can be threatened by flooding and serious coastal erosion.

Approximately every two or three years, significant sand and dust storms occur. Large amounts of sediment are moved in these events, but in view of their relatively low frequency, they can only be regarded as among the less important geomorphological hazards.

2. The tidal zone

The greatest tidal range in Danish waters is only 2m in the salt marsh region of south-west Jylland. During storm surges, however, the water-surface set-up is very important. Along the North Sea coast, this can amount to as much as 3m above mean sea level. Along the shorelines facing the Baltic and the Kattegat, wind set-up is less but nevertheless can also be significant (up to 1m above mean sea level depending on the wind direction), compared with the tidal range which is here very small - only about 0.2m. If a storm from the north-west, setting up the sea level in the Baltic and interior Danish waters, is succeeded by a storm from the north-east, the resulting surge can seriously affect east-facing shorelines. Normally these do not suffer from erosion or raised water levels: consequently, their level of protection is generally low and in poor condition.

The Danish tidal area between Horns Rev and the Danish-German border, known as the Wadden Sea, is characterised by a tidal range of 1.4m at Esbjerg and 2m at Højer. Except for some low cliffs, total protection is provided (Jespersen and Rasmussen, 1989), but in some sections of minor importance, the dykes can only resist the water set-

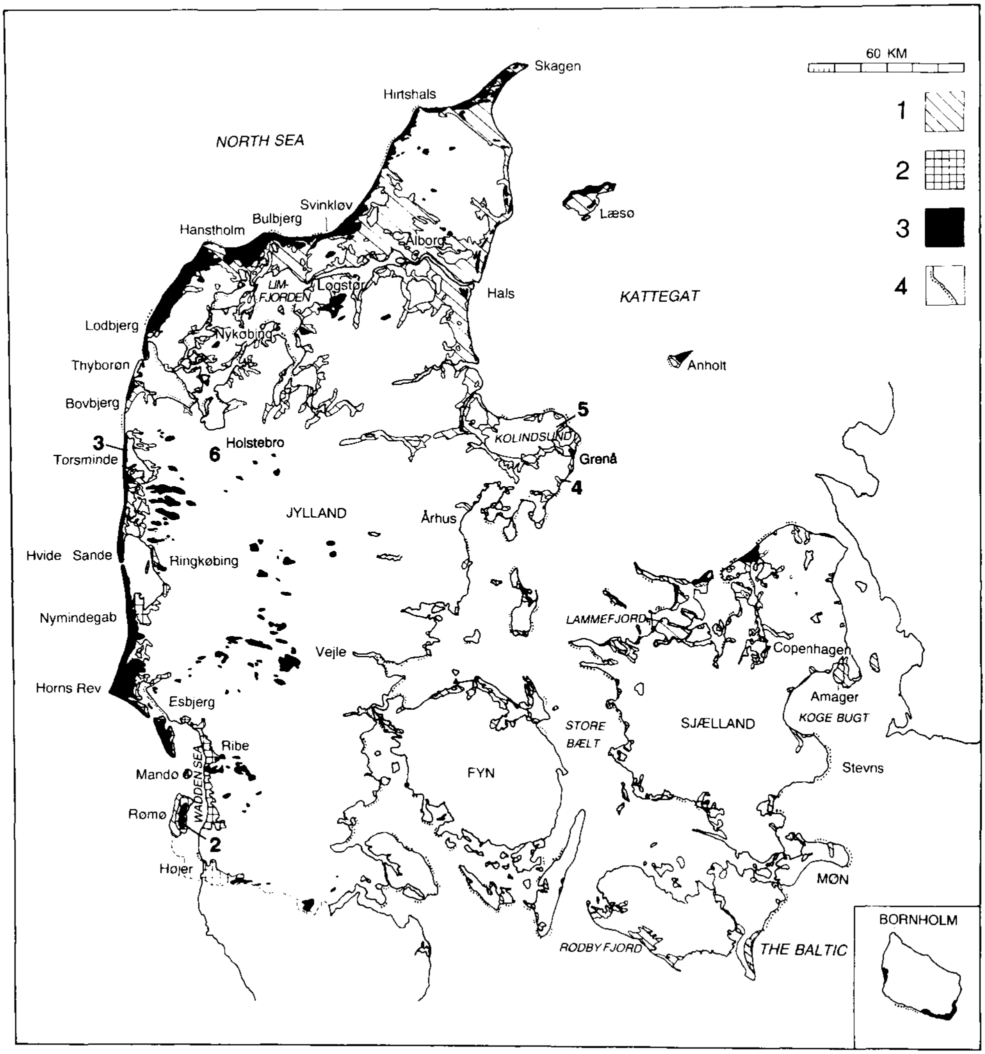

Fig.4.1. Location map of Denmark, showing a simplified distribution of some surface deposits. 1 - post-glacial raised seafloor; 2 - salt marsh; 3 - dunes and blown sand; 4 - coastal cliffs. The locations of Figs.4.2 - 4.6 are shown by the numbers.

up during average storms. Land outside the dykes and land protected by only low dykes can suffer severely. In 1976 (Fig.4.2) and again in 1981, the fishing port on Rømø was completely inundated when the sea surface rose to about 5m above mean sea level (Møller, 1988).

Fig.4.2. The fishing port of Rømø devastated after a storm in January 1976. In the far background, a fishing vessel can be seen dumped on the pier owing to the high water level which overtopped the white bollards. The fishing vessel in the centre foreground has its stern resting on the pier and its bows on a sunken ship. The water level is still high: normally, the decks of the ships lie below the level of the pier.

All sorts of harbour construction works and installations in the tidal zone are frequently flooded; most, however, are designed in such a way that some flooding is acceptable. The local people have also adapted to recurrent flooding and will immediately take suitable precautions against the consequences when warnings are given.

3. The North Sea coast

Owing to the predominantly westerly winds, the typical Danish North Sea coast consists of a sandy beach in front of dune ridges. The beaches naturally suffer from erosion from time to time, but because of the existence of some stable points or promontories, erosion diminishes when the amount of indentation between them reaches a certain size. Further, a sandy shoreline can suffer much from erosion without serious consequence so long as it is backed by dune ridges and that there is a buffer zone inland of the dunes.

Such protection does not exist on the barriers west of the embayments at Ringkøbing, Torsminde and Thyborøn (Møller, 1992). Consequently, as the worst possible disasters can be expected in these localities, large investments in coastal protection are being made here. The channel between the North Sea and the embayment of Nissum Fjord at Torsminde is one of the most dangerously exposed sections of the shoreline. South of the channel, the barrier is very narrow and strongly eroded. Traditionally, the west-coast fishermen have been using the entrances to such embayments as landing places. To improve the landing conditions, a harbour was constructed in the barrier itself, leaving only a narrow strip of land with a dyke as the only protection for the harbour (Møller, 1984). The dyke is now reinforced with a relatively steep sea wall, which has the unfortunate effect that the wave run-up is considerable. In storm conditions, the waves can overtop the dyke and undermine its more vulnerable eastern side (Fig.4.3).

Fig.4.3. A dyke overtopped by waves, west of the fishing port of Torsminde (March 1990). The seaward side of the dyke is to the right (south); north of the small shipyard is a basin partly filled with sand transported across the dyke. Facing the North Sea, branches have been planted in a fence to prevent transport of blown sand, but most of the sand has been carried over the dyke by waves.

On shorelines to the leeward of coastal protection works, the problem of increased erosion resulting from the interruption caused to longshore drift is a severe one. This has occurred in relation to most Danish harbours on exposed coasts, especially those facing the North Sea. Many protection works have been extended to prevent erosion of neighbouring sections of coast (Bruun, 1954). The only possible countermeasure is further protection - of the entire shoreline if the hinterland consists of dunes, but construction and maintenance of coastal protection works is so expensive that total protection of the entire shoreline in this way is out of the question.

4. Cliffed coasts

In a few parts of Denmark, the limestone cliffs and other hard-rock coasts are little affected by man (Møller, 1988) and present few hazards. The most important limestone cliffs situated on Møn, Stevns, Bulbjerg and Svinkløv are now protected by law. Some parts of the cliffs present a potential danger to tourists and have been fenced.

Coastal cliffs composed of moraine or occasionally Tertiary deposits present great problems of erosion. Since Denmark is relatively densely populated, many summer resorts have been developed on the highest points in attractive regions such as northern Sjælland. Since no erosion can be tolerated in developed sites, the owners demand expensive coastal protection works, preferably wholly or partly paid for by the Government. Because of the expense, they are restricted to the most valuable parts of the shoreline in terms of tourism, and these in turn tend to become intensively developed.

5. Sand storms

Most storms in Denmark come from westerly directions, but the comparatively few which arrive from the east cause a great deal of sand drifting and dust storms because they mostly occur during spring, before the cultivated land has been covered by crop growth. Fluvial and glacifluvial deposits cover large parts of Denmark (Møller, 1986) and act as sources for drifting sand (Fig.4.4A), but clayey deposits can also contain high contents of sand, providing another source.

Drifting sand can damage vegetation and crops by wear and tear, and by its accumulation in sheltered places (Fig.4.4B), but the most serious damage results from the removal of fines including organic matter from the soil (Møller, 1986).

6. Inland flooding

This is not normally a serious hazard in Denmark because of the well-drained character of much of the land consisting of meltwater deposits or moraine from the Quaternary, and the relatively small sizes of drainage basins. Occasional flooding connected with rapid snow-melt or sudden heavy precipitation can lead, however, to

overflow of water courses, most of which have very low gradients. In 1970, for example, the stream through Holstebro was flooded (Fig.4.5). In this case the level of damage was high because the road embankments normally retaining the water here, collapsed because of faulty construction.

Fig.4.5. Flooding in Holstebro in March 1970. The high-water mark can be clearly seen on the wall of the house to the right. The basement of the house was filled with water-transported sand. Large parts of this town, which had never suffered from flooding before, were badly damaged and the people had to be evacuated.

Fig.4.4. (*page 96*) A (*upper*): Drifting sand appearing as a cloud over a field on sandy moraine, despite the shelter belts, woodland and a surface roughly tilled for agriculture. Location: south-west of Grenå in September 1988.
B (*lower*): Sand drifts across a road north-west of Grenå after a storm in May 1991. From time to time, the sand deposits can be so large that the roads can only be kept open with snow-clearing machines.

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FINLAND

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1. Introduction

In terms of geomorphological hazards, Finland must rank as one of the safest countries in the world in which to live. Earthquakes are very rare and have never been known to exceed 4.9 on the Richter scale (Ahjos et al., 1984). Volcanism is unknown, and the same is true for such phenomena as tsunamis, major landslides and extreme droughts and storms. No deaths are known to have occurred directly as a result of geomorphological hazards, although material losses caused, for example, by slope wash in intensively cultivated fields (e.g. Mansikkaniemi, 1982) or by mass movements in sensitive clay areas (Aartolahti, 1965) have, in economic terms, locally been serious.

Assurance of livelihood in Finland holds good only for the recent past. Formerly, when life was highly dependent, for example, on successful harvesting, risk was an annual phenomenon. It is only necessary to go back to the 1920s to find that, after a major harvest failure, bread was made from pine bark in many places in northern Finland. To take another instance, there was a total crop failure in 1867; in the subsequent year, up to one-fifth of the population in some municipalities died of hunger following epidemic illnesses (Turpeinen, 1986).

Crop failures no longer lead to famine, but they still form the principal source of financial loss inflicted by natural hazards in Finland. Being caused by climatic hazards such as late night frosts, excessive rain, drought and exceptional winter conditions, crop failures will not be dealt with in this chapter. The remaining losses are chiefly caused by one geomorphological agent, namely river flooding, on which this chapter concentrates (Koutaniemi, 1992).

2. Flooding

Floods in Finland may originate from one or more of the following causes: i) spring snowmelt, ii) warm winter spells, iii) heavy summer and autumn rain, and iv) ice jams, frazil ice and icing. The most common cause is snowmelt (Kuusisto, 1986, Fig.6a) after the long winters, lasting 5 months or so in southern Finland, 60°N, and 8 months in the north, 70°N, measured from the time of the first snow to the time when it disappears from open fields (Solantie, 1987a, maps 20b/h).

Accumulation of snow often leads to a situation in which over a half of the annual river discharge is lost in a short flood period (e.g.,Koutaniemi, 1984). In areas poor in lakes, the discharges of daily flood peaks can be several thousand times greater than the smallest discharges ever measured (*National Water Board*, 1980; Mansikkaniemi, 1986). The second type of flood to inflict severe financial loss is that caused by sudden summer and autumn rain.

Warm winter spells represent a relatively new type of source for floods and may be, as many assume, the first signs of new weather patterns linked to the greenhouse phenomenon with its pronounced effects in high latitudes (Hyvärinen and Leppäjärvi, 1989).

Floods related to ice jams are of comparatively minor importance but locally, for example, in the case of low-lying summer cottages, they can cause serious financial losses. The jams are often associated with frazil ice which increases the danger of abnormally high flood peaks (Perttunen and Puupponen, 1978). Icing is a special phenomenon of winters with thin snow cover and appears in small streams after the whole stream has frozen to the bottom. This may cause local damage to roads, for example, but is of little economic significance on the whole.

In forecasting the severity of floods, one of the most important indicators every winter and in the early spring is the increase in the water equivalent of the snow cover. This is monitored at 154 observing stations of the National Water and Environment Board, and the public is informed in the daily news when the situation becomes threatening.

2.1. Factors favouring floods

In addition to rain, snow, ice and warm winter spells there are several factors that, in the long run, have had an important influence on flooding. Among the long-term phenomena, the most significant is the post-glacial land uplift which, at the present rate, is enlarging the surface area of Finland by about 1000km^2 per century (Hyvärinen, 1985). In the short term, the greatest non-climatic influence is human activity.

Land uplift associated with tilting of the Earth's crust in Finland is the result of heavy ice loading during the glacial periods. Drainage conditions are rendered more and more difficult over time since in general the rivers flow towards the centre of maximum land uplift (9mm a year) in the area of the Gulf of Bothnia (Fig.5.1).

Lake Oulujärvi, the fifth largest lake in Finland, is an excellent example of what has happened with drainage systems flowing in an opposite sense to the direction of tilting. In this particular case, the central basin has doubled its surface area since it was isolated from the Baltic Sea over 8000 years ago (Koutaniemi and Keränen, 1983). The role of land uplift is also well demonstrated by the fact that the majority of the southern inland lakes once had their outlets to the north-west (the Gulf of Bothnia), but owing to land tilting, new courses have been formed directed towards the south-east (the Gulf of Finland) (Saarnisto, 1970).

In brief, land uplift has changed flood behaviour in all the waterways of Finland since the very beginning of the Holocene, and will continue to do so in the future, slowly but effectively.

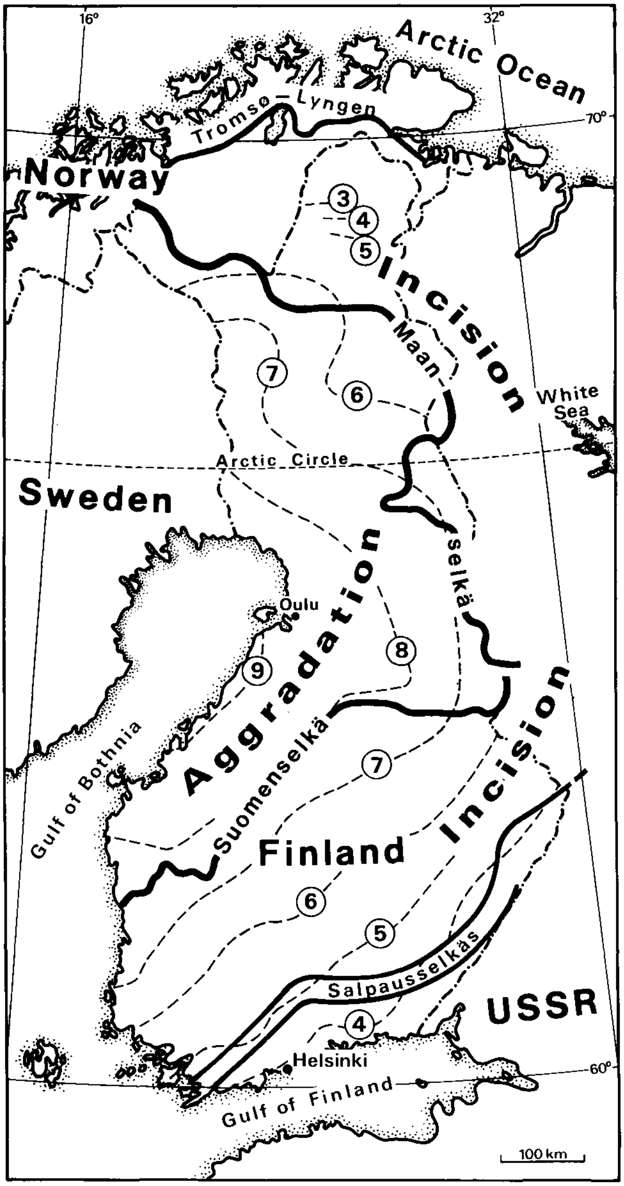

Fig.5.1. Present rates of land uplift (mm/year) in Finland, the Younger Dryas terminal formations of Tromsø-Lyngen and Salpausselkäs, and the main tendencies (incision, aggradation) of Holocene fluvial activity in relation to the main watershed (Maanselkä-Suomenselkä) (Koutaniemi, 1987)

The role of Man in changing river discharges dates back to the second millenium B.C.(Tolonen, 1978), but in a more practical sense, Man's role in changing the flood behaviour of rivers was initiated by the lowering of lake levels. This activity, which reached its peak in the 1850s and 1860s, was stimulated by the increased need for new agricultural land. The second, more intense phase for the same purpose was after the Second World War when close to half a million people had to be resettled from the areas lost to the Soviet Union (Hyvärinen, 1985).

Although frequently undertaken by specialists, lake drainage ended many a time in an unexpected manner, for instance when the current of water ran out of control, resulting in drastic changes in drainage. This was the case, for example, with Lake Höytiäinen in 1859-60 (Fig.5.2), whose water level was lowered by 9.6m at the same time

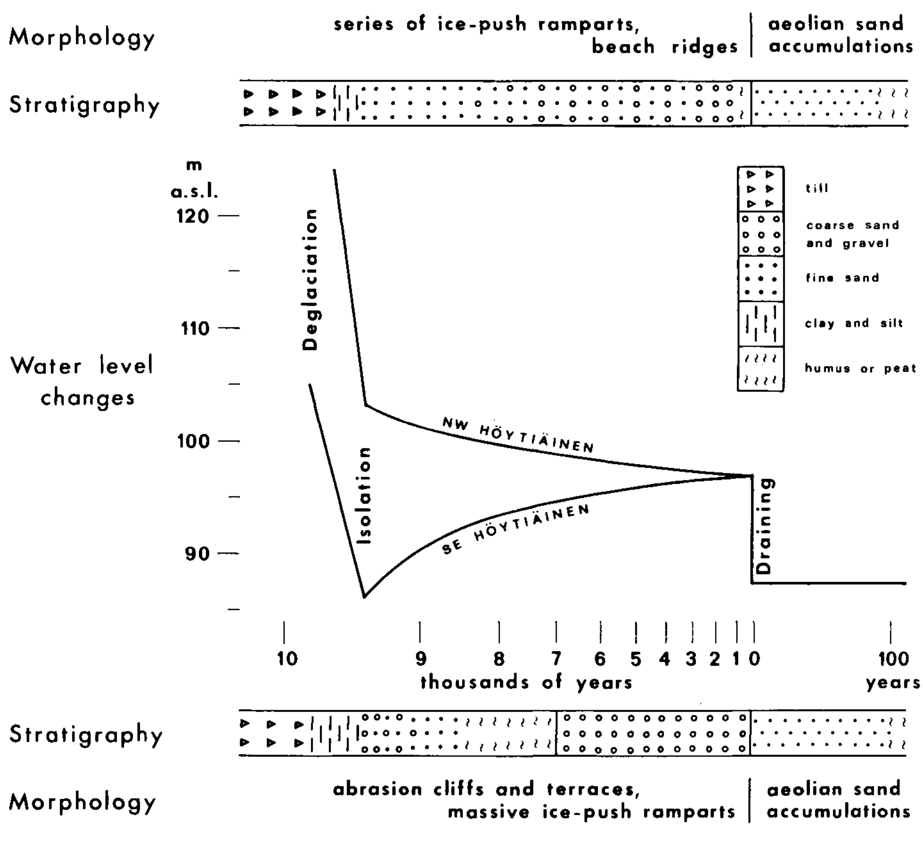

Fig.5.2. The role of isostatic land uplift and Man in controlling water-level changes and the shore morphology of Lake Höytiäinen (Vesajoki, 1980)

as its surface area decreased from 440 to 285km^2, leading to many subsequent environmental changes (Vesajoki, 1980).

Between 1700 and 1960, lake drainage decreased the total lake area by about 2 per cent (Hyvärinen, 1985), and particularly in areas with only a few lakes, these measures

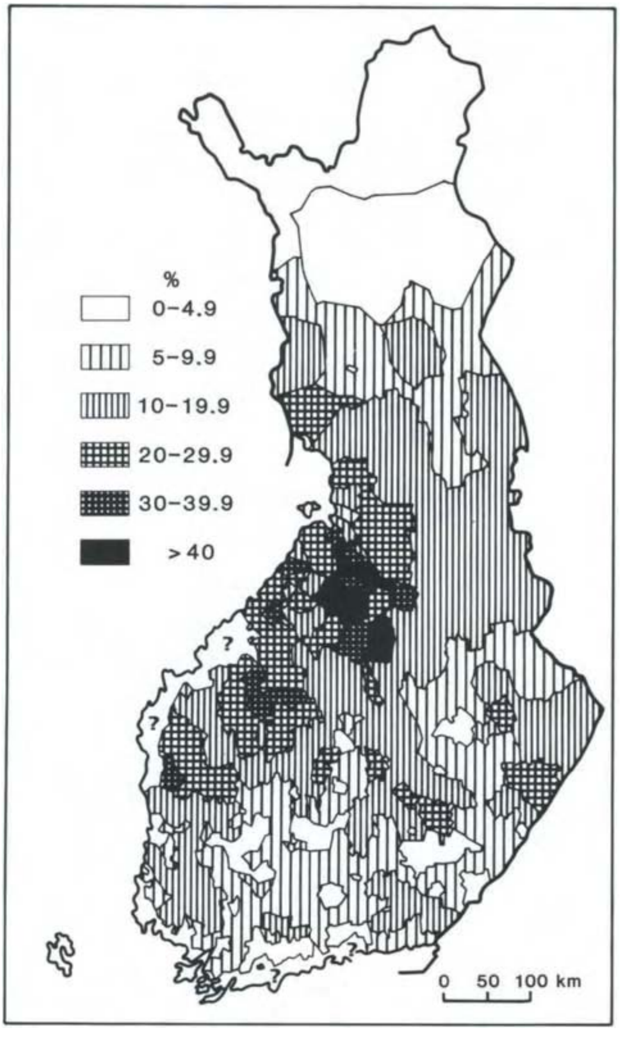

Fig.5.3. Percentage of forest drainage in relation to surface area, by commune, to the end of 1987 (unpublished data from Forestry Board Districts). Areas with question-marks: no data

were to promote a rapid increase in flood peaks. According to Kaitera (1949), mean annual peak discharges have in some cases increased by up to 100 per cent.

Another important human activity has been forest draining, the need for which reflects the strong dependence of the Finnish economy on forestry. Of the total forested land area, peat bogs, where tree growth suffers from a high groundwater table, account for no less than 37 per cent (Kuusela, 1976).

Ditching of forests is concentrated in areas with the greatest number of peat bogs, namely along the coast of the Gulf of Bothnia (Fig.5.3) where changes in drainage conditions have in places been dramatic. In the case shown in Fig.5.4, human activity has raised the drainage density from 0.26 km/km^2 to 16.2 km/km^2: in other words, the man-made value is more than 62 times higher than the natural value - and these figures fail to include drained fields and small-scale ploughing in forest areas to improve the growth of young trees. Since this coastal zone has always suffered from floods and, on the other hand, the effect of forest draining is to increase the mean and maximum discharges (Hyvärinen and Vehviläinen, 1980; Seuna, 1981), improvement in tree growth has been obtained at the cost of the danger of increased flooding.

In addition to lake and forest drainage, there are several other activities that have increased the risk of flooding, such as the dredging of rivers and rapids for improvement of navigation, timber floating and tar transport. Since these three activities have now lost most of their economic significance, much attention has recently been paid to rebuilding the river channels back to their original form.

2.2. Flood damage

Chronicles and other documents record that in the eighteenth century there were at least 8 years with severe floods in Finland. In the following century, every seventh year was difficult, and in the years 1825-26 and 1836, for example, floods occurred throughout the country. In this century, the worst floods were felt in 1924, 1955, 1962 and 1974-75 (Tulvavahinkotoimikunta, 1975).

As stated above, flooding causes the second highest economic losses of all natural hazards in Finland. The most serious is crop failure; the ratio between this and flood damage is approximately seventy to one. This and many other numerical data can be found in a report *Maatalouden tulvatyöryhmä* (1990). Of the total financial losses (70 million FIM, or about 17.5 million U.S.dollars) for 1974-88, over a half (59 per cent) relate to cultivation (Fig.5.5). The second largest group relates to building damage (35 per cent), the remainder being spread fairly evenly among gardens, forests, soil and other personal property.

Comparing the 1970s with the 1980s, there is a noticeable increase in flood damage. In the 1970s, losses per year (on average, 0.9 million FIM per year) were less than one-ninth of those for the 1980s (7.7 million FIM per year). All this is in clear contrast to the forecast lowering of flood heights in Finland (Koutaniemi, 1991), although lower-than-normal flood peaks do not necessarily mean lower risk, owing, for example, to the danger of increase in frazil ice.

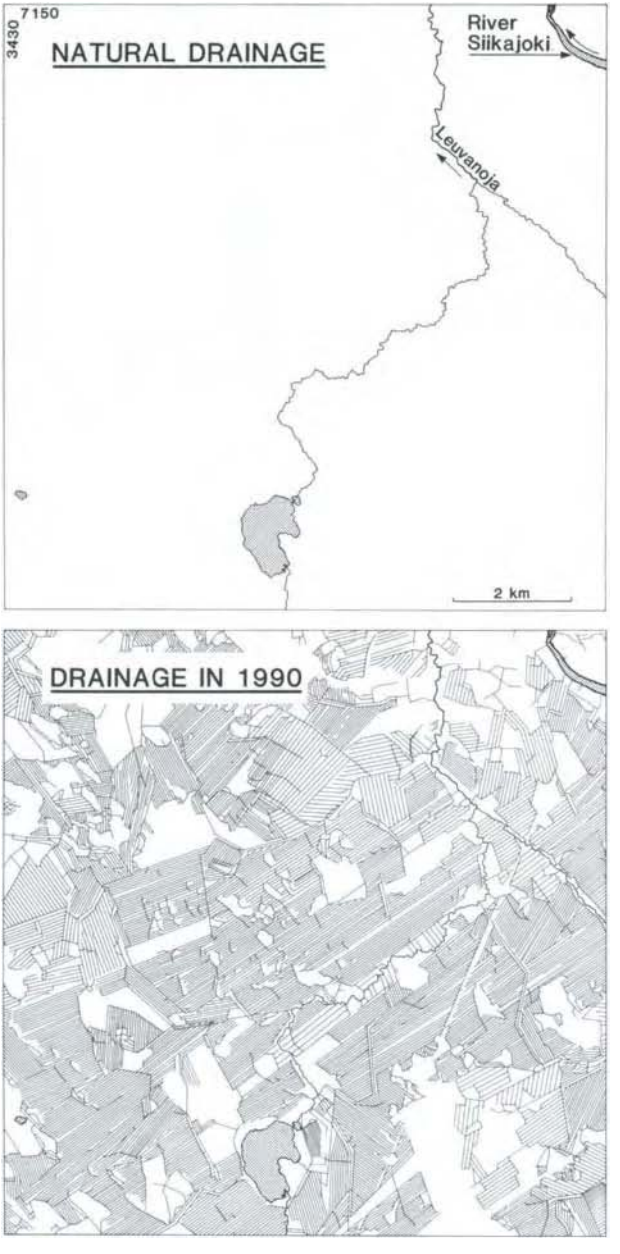

Fig.5.4. System of drainage ditches in one of the most intensively drained areas, Basic Map 341205, near the Gulf of Bothnia

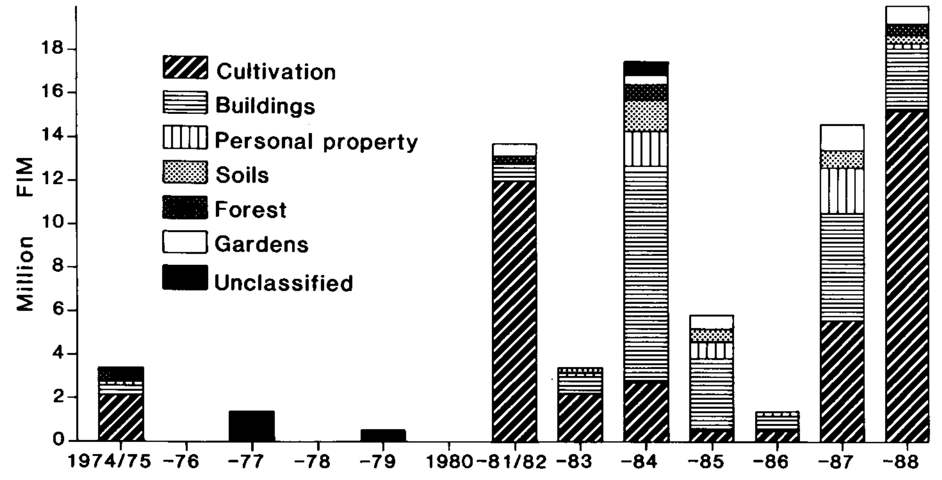

Fig.5.5. Flood damage in Finland, 1974-88. Note that the category "cultivation" includes only damage compensated on the basis of the Flood Damage Act, not the Crop Failure Act.

The regional picture of flood damage clearly reflects the most problematic places in Finland, located in the low-lying coastal zone along the Gulf of Bothnia. Hazardous snowmelt floods in this area are the rule rather than the exception, whereas farther to the north, flood damage is closely linked to the occurrence of unexpected ice jams. For instance, a single jam coinciding with raised floodwater levels at the mouth of the river Simojoki in 1987 destroyed housing to the value of 2.3 million FIM (*c.* 0.6 million U.S.dollars) which accounted for 70 per cent of all housing damage for that year in the whole country.

In one particular respect, flooding and the Finnish life-style form a risk-bearing combination. Every Finn must have a summer cottage and a sauna, both as close as possible to a river or lake. Although it is impossible to obtain compensation from insurance companies in a case of flood damage, and rather uncertain from the community, people prefer to take the risk and build on all-too-vulnerable low-lying localities. The result is to be seen every year in the large number of holiday cottages destroyed or damaged (Koutaniemi, 1992).

2.3. Flood prevention

The first official steps to prevent flood damage were taken by "The Board of the Royal Rapid Dredging", founded in 1799. Nowadays, the most important measure of flood prevention is the regulation of river discharge mainly by means of dams, embankments and reservoirs. So far, about one-third of all drainage systems are controlled to varying degrees (Ollila, 1986).

Flood prevention measures have been mostly undertaken since the Second World War. The work was greatly stimulated by the pressing demands from heavy industry for hydro-electric power, needed to cope with the payment of war indemnities (Florek et al., 1987). Power demand and flood prevention have thus developed hand in hand, but other subsidiary interests have also encouraged flood control. Of the present regulation works, about one half are related to hydro-electric power production as well as flood control, a quarter are designed primarily for flood control, and the remainder are linked to different combinations of these two with water supply needs, timber floating and recreation (Ollila, 1986).

The measures taken have been very effective in reducing flood peaks. At its best, this can be seen in the most effectively utilised waterway of Finland, the river Oulujoki, which in its present form is more like a staircase of lakes than a river (Fig.5.6). Reduction of flood peaks by 25 per cent is normal for less intensively regulated rivers (e.g., Kuusisto and Lemmelä, 1982).

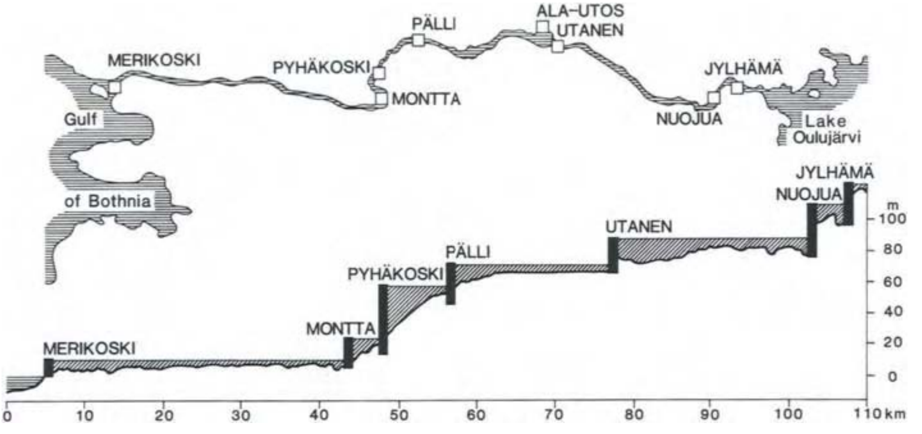

Fig.5.6. Power plants and the longitudinal profile of the river Oulujoki before and after regulation (Florek et al., 1987)

Ice in its various forms is a problem on its own. This mainly concerns the unregulated rivers, since the ice problem is minimal on waterways with a higher standard of construction (Perttunen and Puupponen, 1978). Once ice conditions become threatening, there is little alternative to the use of explosives to break the ice, or the use of hovercraft to try to force the jam to move. Because both of these operations very often result in further serious problems downstream, much attention has recently been devoted to developing new methods of destroying ice covers before they become dangerously thick. Successful measures include the spreading of fine sand or ash on the ice to absorb solar energy and thus weaken the ice cover. Sawing of the ice into pieces has also been used, for example, at the mouth of the river Torniojoki in April 1990, over a length of 25km. This, however, proved to be of little practical help since during the ice break-up, thick sea ice prevented the river ice from escaping seawards, causing serious flooding in the centre of the city of Tornio.

It is typical of the present time that new operations to prevent flooding or to improve other aspects of waterway and water utilisation have met with strong opposition. This reflects a growing resistance of the public to any changes in natural environmental conditions, whatever their primary function.

2.4. Government responsibility

If a crop is destroyed by a severe rainstorm, the farmer is compensated by the state according to the Crop Failure Act (in force since 1975). The amount of compensation varies between 8 and 42 per cent of the crop value. If the neighbouring farmer also loses his crop, but the cause is flooding by a nearby river fed by the same heavy rain, compensation is awarded under the Flood Damage Act (1983) and the amount ranges from 32 to 80 per cent of the crop value.

This simplified example, taken from data given in *Maatalouden tulvatyöryhmä* (1990, 17), demonstrates the paradoxical situation in Finland in 1990 which is that the same disaster can receive compensation on one of two different bases, depending on the interpretation of the cause of the disaster. Not surprisingly, one of the main aims of *Maatalouden tulvatyöryhmä* (1990) organised by the Ministry of Agriculture and Forestry was to decide how crop failure and flood damage could be brought together under the same law.

3. Secondary hazards

Although the word "secondary" is used in the title of this sub-section, it should be appreciated that, to the farmer or other person involved, the phenomena can be locally disastrous. For example, in the long term, slope wash and soil erosion in cultivated areas can be a much greater hazard than crop failure in the short term.

3.1. Frost, snow and ice

Typical of a high-latitude location, freeze-thaw processes play an important role in many hazardous phenomena, such as the slope movements considered in the next section. Ice in the form of ice jams on rivers has already been mentioned, but can also present a minor hazard in the form of ice push on lake and sea shores (Alestalo and Häikiö, 1976). Snow avalanches occur only on a comparatively small scale, given the dominantly low relief of Finland. Permafrost, encountered in the extreme north of Finnish Lapland (King and Seppälä, 1987; Seppälä, 1988) has a scientific rather than any practical significance.

3.2. Slope processes

All slopes in Finland are liable to be affected by solifluction. In normal conditions, such as areas of undulating ground moraine, these processes work so slowly that a human lifetime is hardly long enough for anyone to observe any harmful effects (Söderman, 1980); and of course in inhabited areas the people are accustomed to avoid those places at risk from slope movements.

The situation is quite different along the coast in areas of sensitive clays deposited during the early history of the Baltic. These are areas of intensive landsliding and slumping, processes which Man has intensified by forest clearance for agriculture. Along the river Paimionjoki, for example, Aartolahti (1975) reports up to 20-30 landslides per kilometre. He notes how 500-75 000m^2 of arable land can be lost in a single slide, but that in the most severe cases, the figure can be ten times higher.

Another hazardous phenomenon in the same areas is slope wash. This has appeared fairly recently in connection with the changeover from cattle rearing to exclusively arable farming. Soil losses from the most valuable cultivated land in Finland can reach a level of 6-7 t/ha/year (Mansikkaniemi, 1982).

3.3. Wind damage

Two types of environment are most susceptible to damage from wind as a geomorphological agent: in areas beyond the northern tree limit and in the coastal zone. In the former, the greatest danger is focused on areas of glacifluvial sands (eskers, deltas and sandurs) and relict inland dunes. Recent findings have raised the question whether desertification may be occurring (Kotilainen, in press). Deflation is certainly taking place over large areas (Fig.5.7; Seppälä, 1971) and is partly at least owing to overgrazing by reindeer herds, as well as other human activities.

In the coastal zone, the situation is similar - natural and human agencies are combining to encourage active aeolian processes. In the Kalajoki dune field, which is one of the largest active coastal areas of blown sand, the most active dunes have advanced inland at approximately 1m/year during the past 100 years. In this particular case, the process was evidently started by natural forest fires and accelerated later by tourism (Heikkinen and Tikkanen, 1987). The ever-increasing demands of recreation have also promoted the same problem in inland areas (Aartolahti, 1973).

Levels of wind damage in forests have recently shown an alarming increase (Fig.5.8). The fallen trees are not the only problem: animals have also spread the damage into adjacent areas of sound forest (Saarenmaa, 1989). Wind speeds do not show increased values, but it appears that storms have been occurring more often at a time when the ground is unfrozen (Solantie, 1987b).

Fig.5.7. Reactivated aeolian activity in the Hietatievat inland dune field, Lapland (photo: L.Koutaniemi, 1974)

4. Conclusion

Everyday life in Finland encounters many natural hazards, from floods to ice and snow. People do not make a great fuss about them but take them into consideration and accept their occurrence, otherwise living would be impossible. On the other hand, in a modern organised society, people are better and better protected, for example by government measures against inappropriate plans in house construction. Nevertheless, despite a long tradition of living in the north, people still neglect local conditions; each year lives are lost by venturing on to thin lake ice, for instance.

In respect of the longer term, there is discussion of what changes in the levels of hazard there may be. It is generally accepted by most scientists that, owing to the greenhouse effect, mean annual temperatures in Finland will rise by as much as 5°C by the year 2040 (Boer et al., 1990). This raises many questions, chief among which are:

1) What will be the effects on seasonal ground freezing if the snow cover lasts only 3-6 months, instead of the present 5-8 months (Kuusisto, 1989)? The effectiveness of even a thin snow cover in preventing ground freezing is well known, and an early snowfall is the best protection against frost damage to sub-surface structures such as water mains. This situation may well alter.

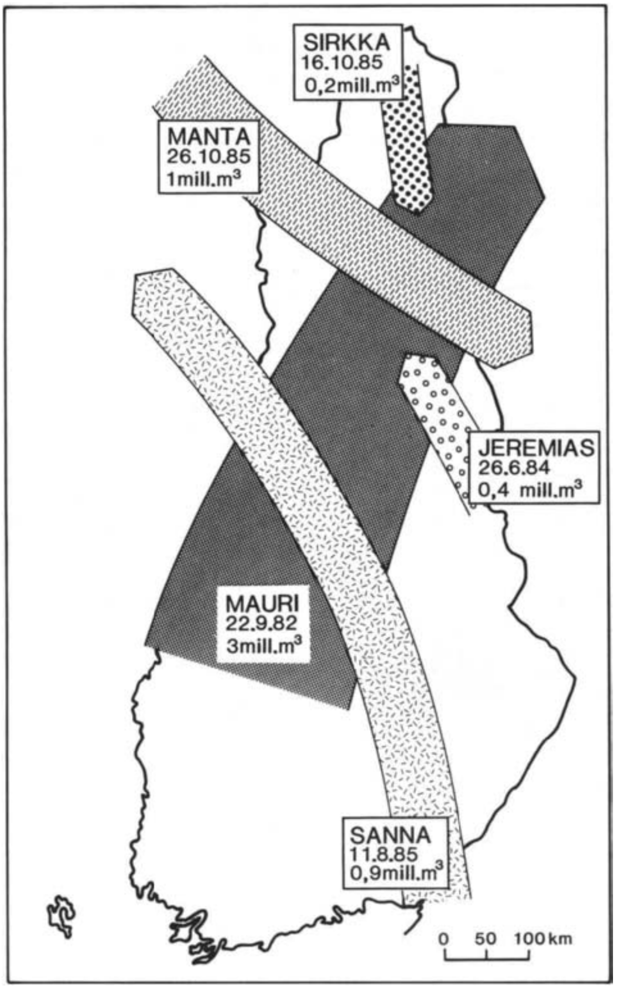

Fig.5.8. Damage inflicted by storms in Finland in the 1980s (redrawn from Jalkanen, 1987). The figures for volume (m^3) refer to the volume of timber felled by the storms.

2) Considering Figure 5.9, one may well ask whether there will be any boreal forest left in Finland by the year 2030. The precise effects on geomorphological processes of such a change are difficult, if not impossible, to quantify, but in general one may speculate that slope processes may be intensified, that runoff will increase as well as the frequency of flood events, and that there may be greater damage from wind erosion.

The first warnings of what the future may hold in store have perhaps already been given. During the 1980s, the weather conditions in Finland were exceptional in many respects. Windstorms, for example, devastated areas of forest greater than ever before (Solantie, 1987b) and the same tendency has been apparent in regard to flood damage. At least two geomorphological agents, running water and wind, have thus already given signs of increased amplitudes of activity which have not been usual previously.

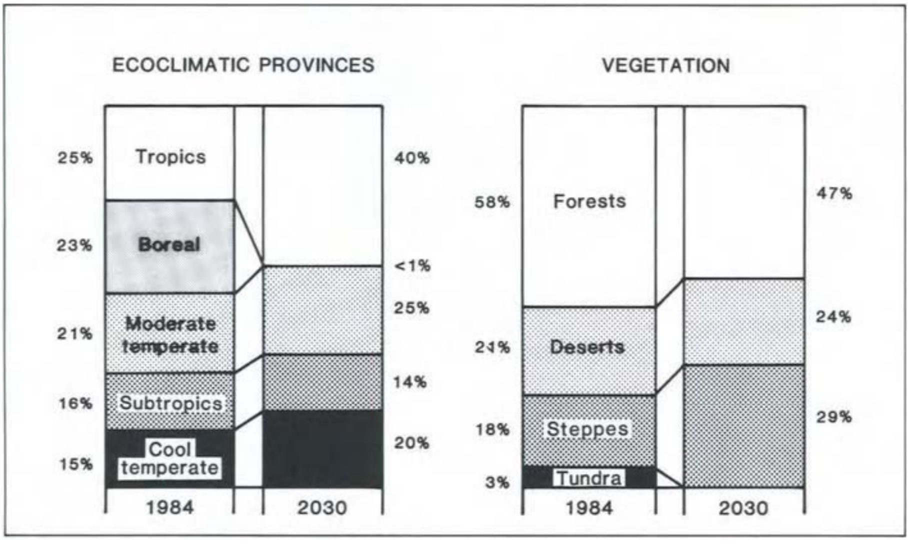

Fig.5.9. Predicted changes in climate and vegetation types caused by a doubling of carbon dioxide levels in the atmosphere (redrawn from *The Greenhouse Gases*, 1987)

On the other hand, there is no other country in Europe that is so favourably placed as Finland in respect of any adverse consequences of a globally rising sea level resulting from climatic warming. Present-day rates of post-glacial isostatic rebound range from 3mm per year in the south to as much as 9mm per year farther north, so that everywhere the land is rising faster than the sea. This situation looks set to continue for at least the next few hundred years, and the future of Finland in this regard is better than for many other low-lying countries.

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FRANCE

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1. Introduction

The mainland of France possesses a great variety of landscapes: old crystalline massifs with extensive planation surfaces, sedimentary basins with limestone and chalk plateaus, alluvial plains, low cuestas and gently sloping terrain, alpine mountains with narrow ridges, high summits, steep slopes and deep valleys, often glacially sculptured, and recent (but no longer active) volcanic areas. In addition, there is a coastline of over 3000km in length facing four different seas or oceans. With an area of 550 000km^2, France presents an array of landform and structure representative of almost the whole of Europe.

Against such a background, natural hazards differ greatly from place to place and in terms of the processes involved. Volcanism was almost entirely confined to the Massif Central and is no longer active in Metropolitan France, though it is still a threat in some French overseas territories; however, a renewal of volcanism in Auvergne could happen at any time. River flooding has in the past been a serious risk for low-lying areas, but nowadays the largest rivers are regulated and controlled. On the other hand, the torrents of the Alps and Mediterranean lands can still cause catastrophic destruction resulting in death, injury and damage to the economic infrastructure, not only by the intensity of the discharge but also by debris flows. Soil erosion connected with human activities comprises a series of natural geodynamic processes that present risks both to areas of intensive farming and to mountainous areas. Coastal erosion is a serious threat to many communities, particularly along the Atlantic and Channel coasts. Studies of the rates of coastal change and on how best to manage this problem are in constant progress.

Glacier hazards are mostly confined to the Alps. Some result from movements of the glaciers themselves, and others from ice avalanches. Snow avalanches are also a source of danger, notably in winter when the level of risk is greatly increased by the concentrations of skiers and tourists. Much work has been and is being done on the definition and mapping of hazard zones in this connection, and on preventive measures for protection. Mass movements, including landslides, rockfalls and mudflows are frequent and sometimes catastrophic events on unstable argillaceous or marly slopes in areas ranging from the mountainous country of the Alps to the actively eroding coasts of Normandy. Mass movement hazards have also been delineated on special maps showing the extent of danger zones and the probability of recurrence.

Major earthquakes are rare in France, but some have been recorded in the past in the Alps, Pyrenees and the Rhône valley where they have triggered mass movements and caused some damage or destruction to buildings and other structures.

Research on the dynamics of rapid geomorphological hazards in France and their impact on human society and economy is increasingly involving not only scientists but also various public and private organisations. Mapping programmes and monitoring of hazardous phenomena, active and potentially active, are contributing to both scientific knowledge and public safety.

2. Hazards connected with volcanism

At the outset, a distinction must be made between the areas of Metropolitan France, where volcanism is no longer active today, and French overseas territories where there are, in contrast, some active or recently active volcanoes.

2.1. Metropolitan France

Although there are no active volcanoes, the possibility (or even probability) of renewed eruptions cannot be overlooked. Volcanic eruptions continued in the Massif Central and its borders from the Eocene to the Holocene - in the case of the Chaîne des Puys (Fig.6.1), eruptions must have been witnessed by early man; phases of activity including the construction of some sizeable volcanic cones alternated with periods of quiescence. The possibility of renewed volcanism is logically most likely in the zones of most recent activity, namely in the Bas Vivarais (Ardèche river basin) where the last eruptions are less than 50 000 years old, and in the Chaîne des Puys (Camus *et al.*, 1990), particularly its southward extension (area of Lake Pavin) where eruptions were still taking place 6000 years ago. Renewed activity in areas of older Quaternary eruptions (such as Devès, Cézallier or the Monts Dore) is less probable but still conceivable.

First of all it should be stated that, contrary to popular opinion, a renewal of volcanism is unlikely to result in eruptions from existing volcanoes (Puy de Dôme, Pariou, etc.), but in the creation of completely new structures. Only in the case of the Monts Dore, representing a composite stratovolcano, is it possible that there might be a return to the same eruptive system and centre.

Major potential hazards consist of three types of phenomena: explosions, lava emission and ash falls. In the commonest situation, involving basaltic lavas, explosive

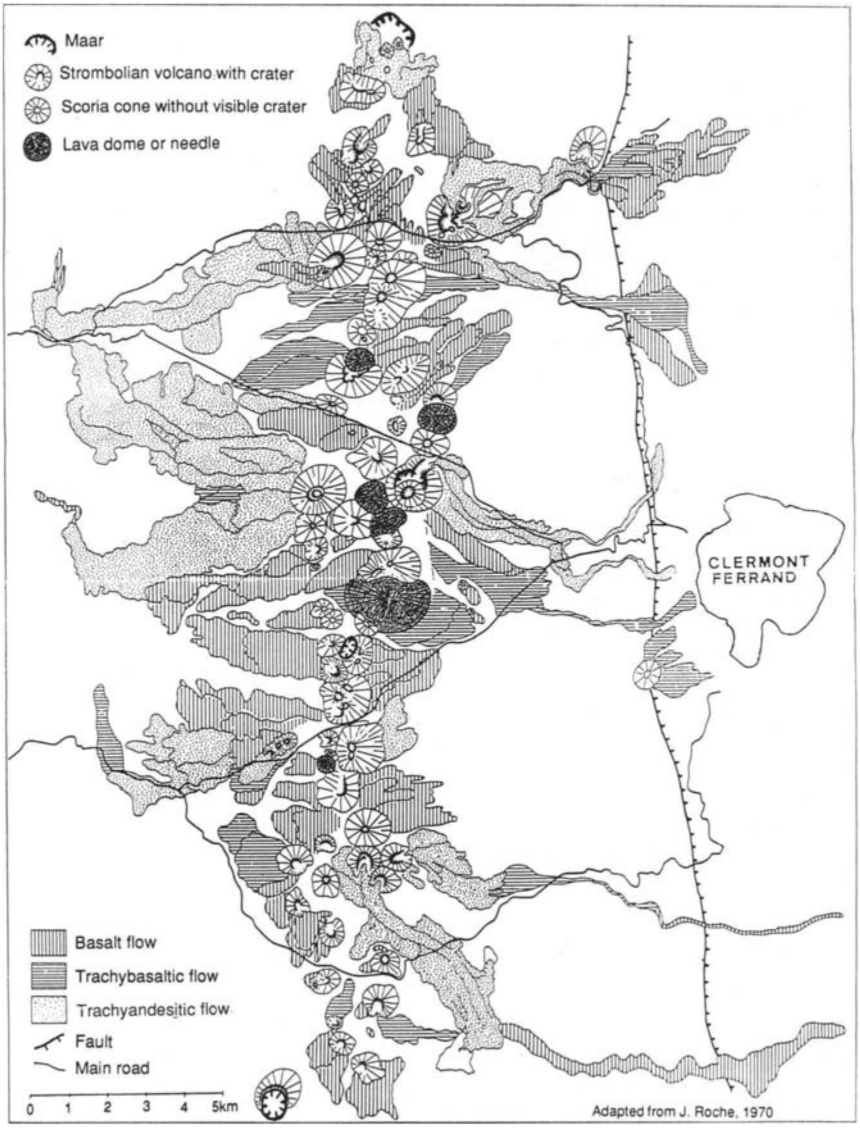


Fig.6.1. Geological sketch-map of the Chaîne des Puys, Auvergne

activity at the outset would herald rapid construction (over a period from a few days to several months) of one or more Strombolian-type cones, regular, breached or nested, as happened with most of the old volcanoes in the Chaîne des Puys. Probably they would grow to imposing dimensions, 100m or more in height and with a basal diameter of hundreds of metres or even more than 1km. A greater risk would be posed by phreatomagmatic activity caused by the meeting of ascending magma and infiltrated water, which is quite common in the initial phases of eruptions. Traces of pyroclastites in the Chaîne des Puys attest to this sort of behaviour. Phreatomagmatic explosions are able to open up large craters in the pre-volcanic substratum and to produce surges ("nuées") of gas and materials travelling with high energy ("déferlantes basales") and capable of transporting blocks, lapilli and cinders for several kilometres.

A more permanent expression of this type of explosive activity would be the creation of *maars*, about 1km in diameter as in the case of Lake Pavin and Gour de Tazenat. Taking the present Chaîne des Puys as a guide, it may be estimated that there is a 10 per cent chance that a future eruption would result in the formation of a new maar. It might be accompanied by one or more cinder cones or by lava flows in the ultimate stages of the eruption after the removal of percolated water. More acid, viscous lavas such as the trachyte of the Puy de Dôme would give rise to lava domes perhaps even bigger than the Strombolian cones of this area, together with explosive phenomena, particularly the emission of *nuées ardentes* (glowing clouds of ash and blocks) able to travel and spread out for several kilometres. In the less likely event of renewed eruptive activity in the Monts Dore, a stratovolcano with acid lavas and a magma chamber that is not perhaps entirely solidified, there could be a cataclysmic eruption and several possible scenarios, such as the occurrence of explosive blasts and debris flows of the Mt St Helens type, emissions of pyroclastic flows and lahars, falls of pyroclastites over wide areas, and even the formation of calderas, thus radically changing the landscape.

The effects of former lava flow emissions are well illustrated around the Chaîne des Puys and elsewhere in the Massif Central (Fig.6.1). Ash falls would affect broader areas, up to several kilometres or tens of kilometres from the eruptive centres. For example, layers of lapilli, scoria and ash from the last eruptions of the Puys, up to tens of centimetres in thickness, can be found in the Limagne. In such areas of ash and lapilli fall, the vegetation is quickly destroyed, creating a desolate landscape.

2.2. Overseas departments and territories

2.2.1. Réunion The island of Réunion consists of two great stratovolcanoes, the Piton des Neiges (3070m), extinct, and the Piton de la Fournaise (2631m), active.

The *Piton des Neiges* became extinct about 20 000 BP and has since been eroded into three broad amphitheatres (the "cirques" of Mafate, Cilaos and Salazie) partly owing to erosion (Kieffer, 1989, 1990). The most recent phase of activity lasted from about 190 000 to 20 000 BP, and was preceded by a quiescent phase lasting several tens of thousands of years during which a deep valley system was eroded. The last period of activity was particularly explosive, with cataclysmic eruptions associated with emission of acid magma and the subsequent formation of a broad caldera (c.10km). It is logical to view the present time as merely a quiescent phase before further eruptions occur. Judging from the previous scale of activity, these could be particularly violent.

The *Piton de la Fournaise* (Bachèlery, 1981; Lénat *et al.*, 1989) is a volcano of Hawaiian type with basic and fluid lavas. It is one of the more active volcanoes in the world, eruptions occurring every few months or years. Though very effusive, it also has violent explosive phreato-magmatic phases, projecting blocks and ash, opening or widening summit craters, such as the formation of the Cratère Dolomieu in 1791. The most common eruptive hazard is related to the development of cracks on the flanks of the summit cone or in the walls of the surrounding "Enclos". The latter is a caldera 8km in diameter, breached by the opening of the Grand Brûlé depression that extends eastward to the sea and stems from a slide of part of the eastern flank of the mountain. It comprises a U-shaped feature in which 95 per cent of the historical eruptions (over the last c. 300 years) have taken place. Over a period of hours to a few weeks, small spatter cones or ramparts (rarely, Strombolian cones) are built up along the line of the crack. Lava can also be directly emitted from cracks without particular constructional forms. These eruptions of pahoehoe or aa lava are confined to the Enclos-Grand Brûlé system, the most important flows running for c.10km to reach the sea and cut the coastal road.

A few eruptions occur out of Enclos, the latest dating from 1977 (Vincent and Kieffer, 1978) and 1986, prior to which there was one in 1800. An eruptive crack spreads out from the central zone across the border of the Enclos, marked by secondary emission points, liberating lava from the depression to the north-east (1977) or south-east (1986). Spatter cones or small Strombolian cones are formed which emit more voluminous flows than those from ordinary eruptions. These flows regularly reach the sea where large platforms of several hectares are built out below the cliffs.

A greater risk, though it has not been known to have occurred in historical times, is evidenced in the geologically recent eruptions on the west and north-west of the Enclos, in the basins of the Rivière Langevin, the R.des Ramparts, the R.de l'Est and even in the Plaine des Palmistes (north-eastern side), which took place along cracks with an orientation N.120°. Here, deep-seated magma welled up to build large structures of Strombolian type such as Chisny. Abundant emissions of lava were channelled along valleys as far as the sea and also spread out in the Plaine des Palmistes.

There is a major risk that the massive slide on the eastern side of the volcano could begin to move again. The likelihood of this happening is not known, but judging from studies of Hawaiian volcanoes (Lipman *et al.*, 1988), it could be extensive, rapid and cataclysmic. As well as the opening and enlargement of many depressions such as the Grand Brûlé, huge volumes of debris would flow into the sea, extending perhaps more than 10km offshore (as happened once before), and producing a gigantic tsunami which could devastate Mauritius as well (Moore and Moore, 1984; Moore *et al.*, 1989).

2.2.2. Martinique and Guadeloupe Each of these islands possesses a similar active volcano of explosive type, emitting viscous andesitic lava. Mt Pelée (Martinique) and La Soufrière (Guadeloupe) are parts of two great volcanic units, each being essentially pyroclastic and of stratovolcano type, and covering much of the surface of each island (Westercamp and Tazieff, 1980; Westercamp, 1983).

Mt Pelée (Boudon and Gourgaud, 1989; Bourdier *et al.*, 1985) is famous for its nuées ardentes such as those of 1902 and 1929, but the greater risk lies in phenomena associated with the evolution of an active dome. As well as the classic clouds of rubbly material able to cover distances of several kilometres (*nuées à blocaux*), blasts of materials at high temperatures and great velocities could occur (blasts or ash hurricanes). It was blasts of this type that destroyed the town of St.Pierre on 8 and 20 May 1902, depositing 1-2m of ash and blocks. Some 29 000 people were killed in this catastrophe. The ash and cinders that blanketted the surrounding country in turn provided material for lahars: in the 1902 eruptions water was available from a summit lake. Today, the asymmetry of the peak suggests that the western side is the most potentially dangerous, at least in the early stages of an eruption, but the risk in other directions cannot be discounted, particularly if the growth of the dome allows it to dominate the other sides. The *nuée ardente* of 30 August 1902 (when the volume of the dome which had appeared some months previously had noticeably increased) devastated a considerable area and resulted in numerous deaths in the area to the east of that affected by the nuées and blasts that destroyed St-Pierre.

Judging from the events of the recent past, other dangers may exist. Plinian eruptions, as happened only a few centuries ago, would bury considerable areas under pumice falls, decimetres to metres in thickness. Phreatic-induced processes could liberate debris flows (debris avalanches), cause blasts and create a caldera of the Mt St Helens type, similar to that located on the south-western part of the massif. Such eruptive activity would also release numerous lahars, but the risk of lava emissions is very small, though possible. Nevertheless, the overall hazard is considerable, for some 22 000 people now live on the flanks of the volcano.

La Soufrière (Vincent *et al.*, 1979) is a dome characterised by solfatara activity that has continued since the eruption (probably in the sixteenth century) that created it. In the short term, the most probable risk may be illustrated by reference to the phreatic eruption of 1976-77 (also those of 1797-98 and 1837-38). This type of eruption involves an increase in fumarole emissions produced by fault movements under the dome. Infiltrating water penetrates to deeper hotter levels where it is vaporised in sufficient quantity to cause significant increases of internal pressure and explosive emissions of vapour. Cracks and explosive vents develop, together with some limited explosive activity ejecting ash and blocks, and small lahars form. In 1976-77, the risk to the population was judged to be sufficient to warrant evacuation of more than 70 000 people for three months.

In the longer term, there are greater risks from events similar to the cataclysmic eruptions of Mt Pelée - pyroclastic flows, Plinian falls, blast and debris flows, lahars, and possible formation of collapse calderas or debris-flow calderas, finally leading to the creation of domes at the end of the eruptive phase. Because the slopes are steeper, La Soufrière is more threatened than Mt Pelée by forms of eruption such as that of Mt St Helens (Boudon *et al.*, 1984). The most recent eruption of this type dates from about 3000 BP; several others predated this. During these eruptions, it is towards the south-west that the debris flows and blasts are directed, and debris-flow calderas opened, and it is to be feared that a future eruption of this type would affect the same side. It is also to be noted that La Soufrière is more capable of producing lava flows than Mt Pelée: its sides display many thick outpourings emitted within the last few thousand years. It appears that only the southern half of the massif has been affected by the eruptive activity in the last 10 000 years, which suggests that the northern side is relatively secure.

3. Flood hazards and their management

Flood hazards have been responsible for increasing damage in France in recent decades, costing 2-5 x 10^9 FF (about 350-950 x 10^6 U.S.dollars) each year. The cost of protection against large-scale flood events is now so high that society must find new forms of adaptation to this type of hazard. Since 1935, a special law has directed the mapping of flood-prone areas along French rivers. Since 1952, a distinction has been made between two zones: zone A, the zone of high discharge close to the channel, where no construction is allowed, and zone B, the neighbouring "complementary zone" flooded by shallow and slow-flowing water, where some types of construction are allowed (Fig.6.2). Destruction of property by events less frequent than about 10 years is considered "catastrophic" and must be compensated by insurance.

Since the late 1970s, geographers have become increasingly involved in the evaluation of hazards and in the study of natural and human-induced damage on floodplains. This has provided some valuable concepts and techniques for the delimitation of sensitive areas (Fanthou and Gambier, 1991; Gazelle, 1987; Lambert, 1987) and in the promotion of passive defences against floods (Faugères, 1990; Tricart, 1982). Geographical research has also been concerned with the generation of floods at the drainage-basin scale (for example, Cloots-Hirsch, 1987; Humbert, 1985) and with reconstructions of how former societies adapted to flood hazards (Antoine, 1989; Desailly, 1989, 1990).

In order to illustrate some of the dilemmas that have arisen in France during the last decade, two major problems will be selected: the occurrence of flash floods in small catchments of south-eastern France, and the long-term management of some large alluvial floodplains susceptible to extreme events.

3.1. The catastrophic floods in south-eastern France: 1987, 1988 and 1992

Three major destructive floods have occurred in recent years which recall the events of both 1957 in the Guil valley (Tricart, 1958) and 1958 in the Cévennes (when 38 people died):

1) At Grand Bornand, a flood on the river Borne killed at least 23 and possibly 50 people in a campground alongside this mountain stream in Savoy, on 14 July 1987. In the Bornes mountains of the northern Pre-Alps, the gauged rainfall was 93mm in 3 hours over an area of 30km^2 - a 170-year event - owing to the advection of warm air from the south (Bravard, 1988; Meunier, 1990; Comby, 1990). The peak discharge was between

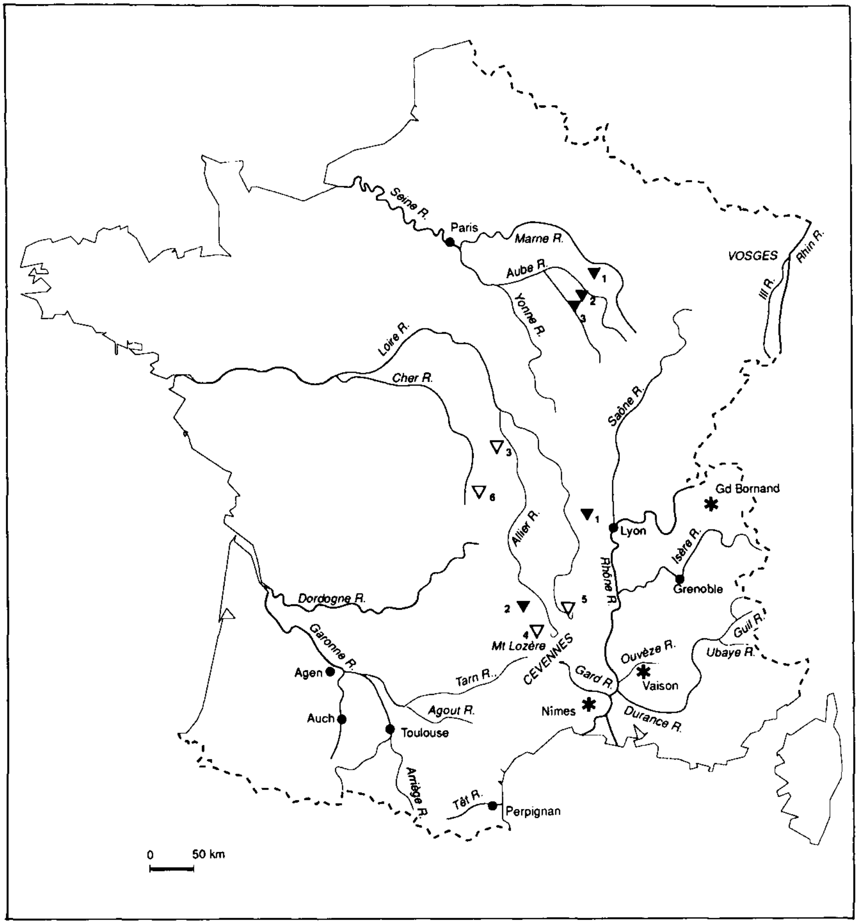


Fig.6.2. Location map. Black triangles: reservoirs in the catchments of the Seine (1 = Marne, 2 = Aube, 3 = Seine) and Loire (1 = Villerest, 2 = Naussac I); open triangles: reservoirs projected in the Loire basin (3 = Le Veurdre, 4 = Naussac II, 5 = Serre de la Fare, 6 = Chambonchard)

225 and 245m^3/s and the total bedload transport was about 47 000m^3. Damage was assessed at 5 million FF (about 1 million U.S.dollars).

2) The flash flood at Nîmes on 3 October 1988 was caused by a stationary rainstorm with a recurrence interval of 150-200 years. In the centre of the event, 420mm fell in 6-7 hours on the karstic plateau above the city, followed ravines draining the city and generated a flood which was made more severe because the catchment (42km^2) was

saturated by previous rainfall. The peak discharge through Nîmes was *c.* 2000m^3/s, with maximum velocities of 7m/s in the streets. Only nine people were killed but 45 000 suffered damage to property totalling 4 x 10^9 FF (c. 750 x 10^6 U.S.dollars) (Fabre, 1989, 1990).

3) The most recent destructive flood at the time of writing was that of 22 September 1992, which killed 42 people in the Department of Vaucluse, including 32 in the small town of Vaison-la-Romaine, drained by the river Ouvèze, a tributary of the Rhône (Fig.6.3). More than 200mm fell in 4 hours over 200km^2 on the slopes of Mt Ventoux which towers above the town, generating a peak discharge of about 650-800m^3/s at Vaison.

These recent dramatic events were the subject of differing interpretations, but there was agreement over the basic causes of the damage. First of all, the rainfall was exceptional for each individual area, though events such as these occur relatively frequently in south-eastern France (Bravard, 1983). Indeed, such Cévennes-type rainfall as was experienced in the Ouvèze catchment has been recorded five to ten times elsewhere in Mediterranean France during the last decade. In three other cases the peak floods may have been the 100-year events on small tributary streams; on the other hand, the town of Vaison was previously flooded by similar events in 1886, 1907, 1916 and 1951 without causing serious damage. The river Borne in fact has registered 38 floods between 1726 and 1951 without any catastrophe on the scale of that in 1987.

The most controversial issue concerns the degree of human responsibility for the recent disasters. This issue has been most strongly debated in the case of the Ouvèze where land clearance for vineyards has been accused of increasing the runoff and where, over the last 50 years, neglect of river channels by farmers (who are obliged by law to keep the channels clean) may have contributed to the formation of log jams which are said to have exacerbated the flooding when they broke (Mennessier, 1992). It is also the case that most of the damage has been the result of inadvisable utilisation and settlement on the floodplains. Runoff from the catchment above Nîmes has accelerated because of surface and vegetational changes, while the use of the "cadereaux" (channels constricted between walls) for camping sites and other tourist amenities has been authorised despite the risks involved.

In a report dated 1989, Vaison was listed as one of 52 French Mediterranean settlements potentially under threat from flooding, yet nothing was done; 2000 camp sites along rivers were considered unsafe, of which 44 are situated in the Department of Vaucluse. In valleys such as these, the local authorities are supposed to compile a *Plan d'exposition aux risques naturels prévisibles (PER)*, according to the law of 1982, which would forbid any building in such cases. The costs of compliance, estimated at 80 000FF in each case, will impose long delays before they are completed. In practice, the public administration has the task of informing mayors of the natural hazards in their areas, but the law on "décentralisation" of 1983 transferred responsibility to local authorities at the expense of state authorities.

There is also the problem of forecasting such extreme events and the response to warnings. In most cases, the reaction to the issuing of a forecast of exceptional rain and

Fig.6.3 A (*upper*): The floodplain of the Ouvèze, looking upstream from Vaison, after the flood of 22 September 1992 (most debris has been removed); B (*lower*): Destruction of a house by the same flood (J-P.Bravard)

the probability of serious flooding has been too slow. For example, at Vaison, exceptionally intense rainfall was forecast as early as 21 September; the rainstorm occurred on 22 September between 12.30 and 15.30, and the rescue operation began at 17.00. Clearly, efforts in this connection must be improved if lives are to be saved. The case of the Gard catchment may be cited; here a network of flood-forecasting sites was set up in the late 1970s by the Ministry of the Environment and the *Direction Départementale de l'Équipement* in charge of this river (Obled and Leoussof, 1987).

Fluvial dynamics also play a not inconsiderable role in the management of steep gravel-bed rivers. On the Isère, upstream from Grenoble, river-bed degradation has been a problem induced by the embanking of the river and gravel extraction. The capacity of the channel was increased, but while this reduced the threat of flooding of the alluvial plain, the risk in Grenoble itself has been heightened (Vivian *et al.*, 1987).

3.2. The management of flood risks in large valleys

3.2.1. The Garonne valley: flood prediction The Garonne valley was devastated by sudden large floods in 1875 (8000m^3/s at Agen), in 1931, 1952 and 1981 (see Lalanne-Berdouticq, 1989; Lalanne-Berdouticq et al., 1989). The flood stage in some of these events may have reached 10m. On the Garonne floodplain, which extends over 800km^2, Lambert (1989) has demonstrated the effects of the alternation of wide and narrow reaches, and of the presence of old submersible dykes, on the discontinuites in the hydrographs of major floods.

Following the system used since 1966 on the Dordogne, the efficient *Service hydraulique centralisateur du bassin de la Garonne* at Toulouse is in charge of flood forecasting. Since 1980, about 100 automatic weather stations have been installed throughout the catchment so as to provide rainfall and waterlevel data every hour. The data are transmitted electronically to terminals, with a 10-minute delay (Couzy, 1989).

3.2.2. The river Seine: choice of upstream reservoirs After the catastrophic floods of 1910 and 1924, a series of upstream reservoirs was constructed in order to protect Paris. They can hold back 13 per cent of the flood discharge and can decrease, by 1.6m, the stage equivalent to the 1910 flood. The main dams are named the Seine, the Marne and the Aube. The 1935 legislation was largely ignored on the floodplains of the Seine and its tributaries, and implementation of the *PER* is late. About 4000-4500ha of residential and industrial estates near Paris are prone to flooding and rely on a forecasting service which was only modernised after the 1982-1983 floods.

In practice, the water from the reservoirs is so useful for diluting the late spring and summer sewage discharge in Paris that the reservoirs tend to be filled during winter, to the detriment of major spring flood control. The case illustrates the conflicts which may arise in complex water management.

3.2.3. The Loire valley: constructing large reservoirs or preserving ecology? In 1979, France decided to turn attention to the development of large valleys threatened by potentially catastrophic floods, and the Loire valley, which was devastated by the 1856 flood (when $1000km^2$ were flooded and damage was estimated at 10^{10}FF in present-day terms: approximately 1.9 x 10^9 U.S.dollars), was considered as a priority. This is a valley which has been devastated by big floods at least once every century, when its normal discharge of some $3000m^3/s$ is suddenly swollen to a raging torrent flowing at more than $9000m^3/s$. In 1707, over 50 000 people were drowned when the river burst its banks, and the following century saw three of the greatest Loire floods on record. Again, in 1856, the river at Tours rose more than 8m above normal. The J.Chapon Report of 1979 proposed an integrated plan for the control of flooding, consisting of (a) the construction of retention dams in the upper reaches, (b) the delimitation of flood-hazard zones (where urbanisation is prohibited) in the downstream areas, and (c) measures for ecological conservation. The building of new embankments, except for the protection of habitats, is forbidden, and the reservoirs designed to reduce high-magnitude flood peaks must not adversely affect the rejuvenation of fluvial ecosystems by the higher-frequency discharge events. The EPALA (Etablissement Public d'Amènagements de la Loire et ses Affluents, an inter-departmental institution created in 1984 as a result of the 1980 flood which caused damage amounting to 400 x 10^6 FF) has given priority to the construction of four reservoirs at a cost of 2330 x 10^6 FF (about 440 x 10^6 U.S. dollars). This programme has been strongly criticised by ecologists who wish to protect the riverine ecosystems intact, as a continuum from the upstream areas to the lower reaches, and the programme has been delayed by the French Government. The controversial dam at Serre de la Fare was cancelled in January 1994, and another at Le Veurdre on the lower Allier has been shelved for at least 5 years. The schemes at Naussac and Chambonchard have, however, been approved.

3.2.4. The Saône valley: protecting the floodplain or preserving ecology? A similar conflict has arisen in the Saône valley. Because of its very low gradient due to Quaternary tectonics, this tributary of the Rhône is liable to flood $2600km^2$ during late winter and spring, causing damage, principally to agriculture, amounting on average to 175 x 10^6 FF (about 30 x 10^6 U.S.dollars) each year. The demand for better protection comes from farmers who recently converted meadows into arable land. Instead of controlling the low-frequency events, which could increase the flood hazard in Lyon, the water authorities decided to protect the floodplain with levees against small floods, allowing some slight overflow (Balland, 1991). Ecologists have protested against such plans which would alter the links between the river and its floodplain; the relict meadows would also disappear to the detriment of a rich bird fauna (Tachet, 1991).

In conclusion, French rivers display a diverse set of conditions reflecting differences of hydrology and response to meteorological events. The contrasting cultural history and uneven economic development of the basins combine to cause variations in the susceptibility of the population to flooding, and may explain some of the delay in dealing with the problem. The emergence of ecological sensitivity is also not easily accommodated within the existing decision-making framework at both state and local levels.

4. Soil erosion

The term refers to the erosional and depositional processes associated with farming, forestry and grazing; these activities can accelerate the natural geological processes. Until about 1970, French investigations on soil erosion were mostly carried out in northern and western Africa, and apart from some mountainous areas, their possible incidence in the temperate environment of mainland France was neglected. In the last 20 years or so, there has been a strong development of interest in this field (Monnier, 1986; Roose, 1984), examining the geomorphological processes involved, the areas affected, rates of operation, the possible consequences for farming in the long term and the measures that can be taken to combat the problem (Auzet, 1987; Jarry, 1987).

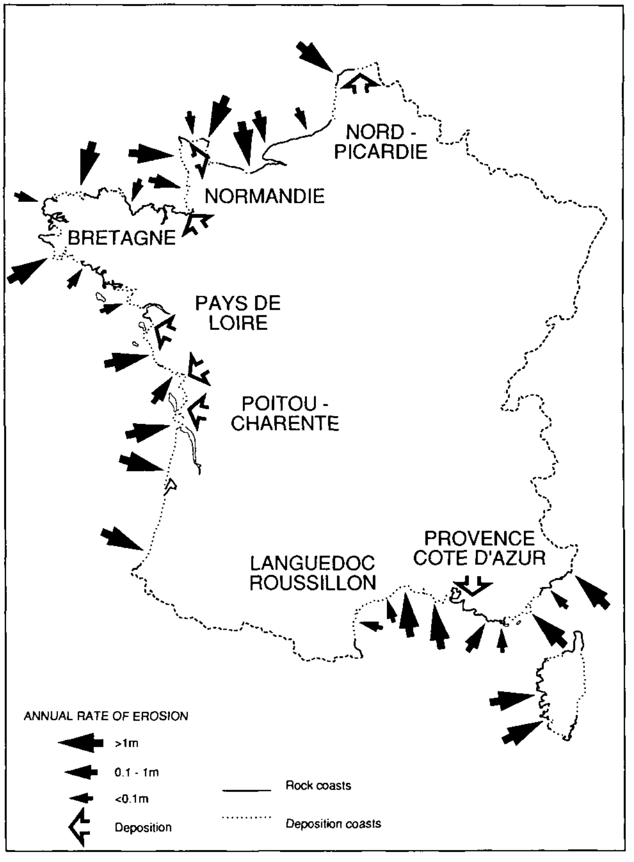


Fig.6.4. Coastal erosion in France according to the Laboratoire Central d'Hydraulique de France (1983)

The growth of interest stems partly from the evolution of modern farming systems that often increase the intensity of soil denudation, and by the damage caused by the corresponding deposition of sediment elsewhere (Olivry, 1988), in areas where little was previously known about the phenomenon. Examples of areas where soil erosion is now recognised include the northern part of the Paris Basin, some of the gentle rolling landscapes taken over by large-scale farming in south-western France, and in areas of specialised farming such as vineyards (Gril, 1986; Vogt *et al.*, 1986).

Current investigations are principally in two fields. First, there is research into historical soil erosion, which is attempting to determine how far human activity was responsible for gullying and the colluvial and alluvial deposits of historical age (Cosandey et al., 1987; Neboit, 1983). A problem is to separate the effects of natural environmental, particularly climatic, change; the present view is that man played a prominent part as a geomorphological agent. Secondly, studies of the basic denudation processes (physical and chemical degradation of the soil mantle, Martin, 1988); runoff erosion, with special emphasis on the effects of cultivation, on slopes in both lowland France and in hilly areas such as the Cévennes (Morand and Wicherek, 1987; Muxart *et al.*, 1986, 1987; Wicherek, 1986); gully erosion and torrent activity; links between the physical erosion processes and the plant cover, process modelling (Muxart et al., 1988) and compilation of soil erosion data are being undertaken. In the field, test plots are being used with either natural or simulated rain (Trevisan, 1986; Jarry, 1987), and experiments at natural scale are being run, coordinated for example in some small river basins in the north of the Paris Basin by the Centre de Géomorphologie at the University of Caen. Large-scale mapping of erosion features (e.g. Dewolf and Joly, 1985; Joly, 1989; Vogt, 1986) has been carried out, in some areas also using aerial photography (Muxart *et al.*, 1988), and satellite remote sensing and airborne radar have successfully been employed to map soil types, soil moisture and other parameters. Many studies are being made to estimate the risk of erosion on cultivated land (e.g. Cosandey and Muxart, 1989; Dewolf and Joly, 1988; Maucorps, 1987).

5. Coastal erosion in France

5.1. Rates of erosion

Cliff and beach erosion represent a serious threat for coastal settlements and infrastructure which have been largely developed over the last 30 years. Figure 6.4 shows the incidence of erosion on the Channel, Atlantic and Mediterranean coasts; the map shows that erosion is prevalent over long stretches of the coast, whereas progradation is restricted to small segments.

Along many beaches, the annual erosion rate is greater than 1m/year. To give a detailed example, Figure 6.5 shows the long sandy beach extending south of the Gironde estuary, where wave erosion can reach as much as 4m/year, according to the average calculated on a 10-year basis (1967-78). In some places, the Landes coast retreated more than 10m in one particular year, 1978-79 which was especially stormy. The Channel coast also exhibits some rapidly receding cliffs, and Figure 6.6 gives a quantitative evaluation of cliff erosion west of Caen. Here, mass movements represent the most important process of cliff retreat. The huge landslide reported at Le Bouffay (Fig.6.7) occurred suddenly on 5 August 1981, and involved more than 10 million tons of rock.

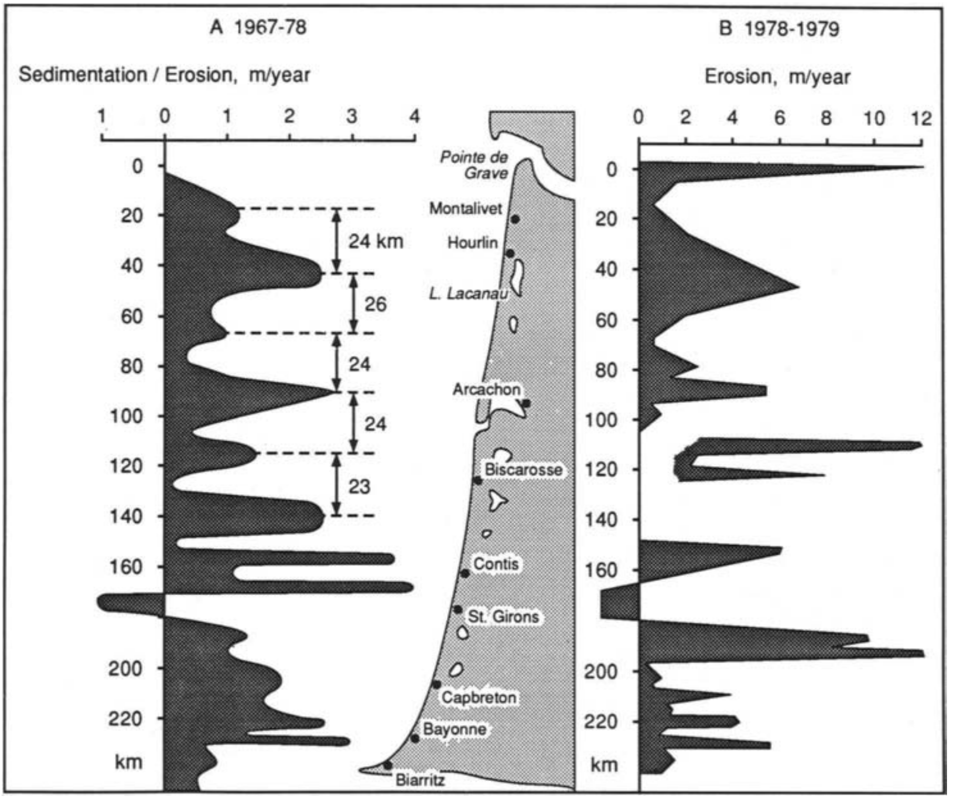


Fig.6.5. Beach erosion south of the Gironde estuary (J.Larin, 1984). Rates of erosion and sedimentation are given in metres per year.

Mitigation of coastal hazards resulting from beach and cliff retreat is mainly based in France on the use of artificial protective structures such as sea walls and groynes.

Considerable use is made of remote sensing in coastal studies in France, particularly in the IMAGEO/CNRS laboratory. The technique is particularly useful for obtaining sequences of images over short time periods, when monitoring rapid coastal changes, especially those hazardous to man (Cuq, 1983; Regrain, 1980).

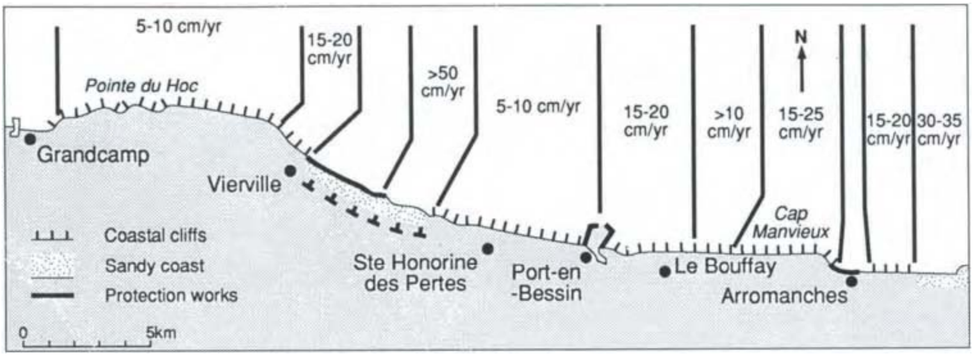


Fig.6.6 Cliff retreat west of Caen, Normandy: annual rate of erosion calculated from a 150-year record (O.Maquaire, 1990). Figures indicate rates in centimetres per year.

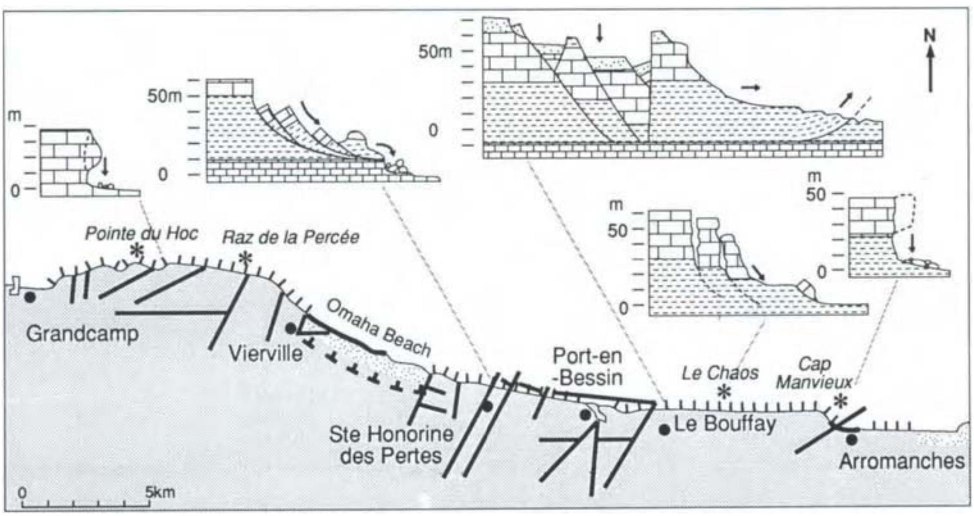


Fig.6.7. Mass movements on cliffs west of Caen, Normandy (O.Maquaire, 1990)

5.2. Coastal management

Increasing attention is being paid to this aspect of coastal dynamics by French geomorphologists and other scientists (Paskoff, 1985, 1992). Man's impact on the coast, interfering with natural coastal evolution, can result in detrimental changes, such as beach erosion, dune erosion and silting of estuaries. There is consequently a need for better understanding of coastal dynamics in order to counteract, or to control more efficiently, undesirable trends.

The sand-dune belt of Gascony is one of the main places of research interest on the west coast of France (see *Atlas des types de dunes littorales des Landes de Gascogne*, 1981; Féniès *et al.*, 1986). Here the focus of investigation is on the degradation of dune vegetation, the rapidly retreating shoreline and the inadequate controls on human settlement and development. Geographers have been working here in close association with other specialists and the official services. Other areas under investigation include the coast between the Gironde and Loire estuaries, especially in the Bay of Bourgneuf (Corlay, 1986), at the mouth of the Vilaine River and in Vendée. In Brittany, particular attention is being paid to the protection of the Holocene coastal dunes and to the measures needed to stimulate their regrowth, for, once destroyed by human activities, these dunes are unable to reestablish themselves by natural processes (Hallegouët *et al.*, 1986). Also being studied in Brittany are coastal evolution during the last 300 years (Cuq, 1987), the rapid retreat of the shoreline in the Bay of Audierne (clearly linked to the human destruction of a shingle ridge here) and conflicts in the utilisation of the coast, as in Morbihan (Miossec *et al.*, 1985). As in Gascony, there has been close cooperation with public organisations and a nature conservation society.

6. Glacier hazards

Despite the limited area covered by glaciers today in France (approximately 400km^2, almost exclusively in the Alps; see Vivian, 1975), they are a considerable source of danger, more particularly so in the case of large glaciers several kilometres long. These dangers stem from a variety of factors: the characteristics of the glaciers themselves, the subglacial meltwater, the movements of the ice or the advances/retreats of the glacier margins. Sometimes the movements are constant or show increases or decreases over years, decades or even centuries. During the last 50 years, tourism in the mountains, mainly in summer but also in winter, has considerably increased the risks and potential dangers associated with glaciers (Bourgeat, 1989; Chardon *et al.*, 1984). The following risks may be identified:

Natural hazards related to the glacier itself. In addition to the existence of crevasses, moulins, surface streams and bergschrunds (often hidden by snow) which are all dangers for alpinists, there are the risks presented by falling seracs, frequent during periods of warm weather and responsible for a considerable number of victims. Ice falls from an ice face are rarer. The collapse of a hanging glacier snout, or a glacier avalanche, as in the case of Le Tour on 14 August 1949, can be another hazard; these situations where the receding front of a glacier overhangs the valley below are not uncommon at the present day.

Natural hazards related to glacial meltwater. These are both the most serious and the most frequent, all the more so since the risk often cannot be foreseen. Surges in proglacial streams and flooding (for example, the Arneyon spate, during September 1920) can be triggered by heavy rain and a rise in temperature. Larger scale catastrophes are caused either by the periodic overflow of meltwater pockets (e.g. the Trient glacier) or, more frequently, to the sudden, unpredictable and sometimes violent draining of englacial, subglacial or marginal water bodies. This was the case in the Tête Rousse disaster (Mont Blanc massif) when, during the night of 11-12 July 1892, an estimated discharge of 200 000m^3 became a torrential mudflow causing severe damage in St Gervais and the Arve valley; more than 100 victims were reported.

Despite progress in glaciology and meteorology, it is not easy to assess the likelihood of such catastrophic discharges. Proglacial lakes can also constitute a threat when they are retained behind a dam of loose morainic material, but they can be artificially drained, as was done in the case of Lake Arsine (Hautes Alpes) in 1986.

Glacier movements are usually slow but can sometimes exhibit a sudden surge, causing serious damage to any structures built on or near to the glacier, such as water ducts, intakes, pylons, ladders and access routes. In 1988, the sudden collapse of the access footbridge to the Mer de Glace (Chamonix, Mont Blanc) owing to a sudden shift of the glacier is a case in point. Advancing glaciers in the nineteenth century resulted in the blocking of several valleys, obstructing their drainage and creating lakes which, because of unpredictable discharges, were responsible for some disasters (e.g. in the case of the Lepenaz glacier, Vanoise, Savoy, in 1818). Such events no longer occur, but the general deglaciation of this century has had its effect in destabilising some valley walls and mountain sides, causing numerous rockfalls and slides (e.g. on the south face of La Meije, Oisans).

It is not only the glaciers themselves but also adjacent areas and valleys below the glaciers that are zones of high risk. This is all the more true when the relief allows the existence of major glaciers. Monitoring and prediction, thanks to advances in glaciology, are now better able to pinpoint the risks and to indicate the most successful preventive or mitigating measures. Dissemination of information to users of high-altitude tourist facilities is essential. The mapping of hazard zones, their demarcation and classification, and engineering works to clear river beds and empty potentially hazardous lakes, are also being undertaken.

7. Avalanches

Avalanches are no new phenomenon; with the development of mountain tourism, and more especially winter tourism, however, the dangers have increased. In France, most snow avalanches occur in the Alps but there are subsidiary areas at risk in the Pyrenees, the Massif Central and the Jura. Avalanches are categorised according to guidelines laid down by UNESCO (see also ANENA; Rey, 1986):

Fresh snow avalanches. These consist either of dry powder snow in conjunction with powder clouds or crumbly slabs when cohesion is weak, or of wet snow. In the latter case, movement can be rapid (50-80km/hour) and they can occur on slopes of $< 15°$.

Powder avalanches with clouds are a special case, not only because they alone follow a straight path, independent of the surface topography, but also because they have a turbulent flow. They can attain high velocities, over 100km/hour, stripping and even uprooting trees when the whole snow layer is in motion.

Slab avalanches are the product of old snow, which is often hard, and consist of variable-sized blocks. They create a downhill thrust which activates the snow lower down and frequently occur on slopes of between 25° and 40°. They are highly dangerous for both piste skiers and cross-country skiers, and are responsible for many victims each year.

Thaw avalanches are frequently deep and occur especially in spring. They set in motion large quantities of densely packed wet snow which erodes avalanche tracks and forms avalanche cones in the run-out zones. The high densities attained (600kg/m^3 or more) in the run-out zones accounts for the fact that they melt late in the season; sometimes the consolidated snow survives from one season to the next.

Mixed avalanches are those in which flow conditions are modified according to the topography encountered during the descent.

7.1. Avalanche risks and impacts

Because of the huge masses of snow often involved and the speed of flow, avalanches are a continual source of danger (Valla, 1990). They may cause partial destruction of forests and slope erosion, which render the exploitation of certain zones impossible. According to Bravard (1990), between the year 1000 and 1971, the avalanche log-book

Fig.6.8. Buildings destroyed by snow avalanches, 20 January 1981, in Saint Colomban-les-Villards, Savoy (photo: F.Valla)

of the *Agents des Eaux* recorded 23 831m^3 of accumulated deposits for the Chamonix valley alone. Roads may be partially or completely blocked; sometimes motorists are trapped in their vehicles (this caused four deaths in 1978 on the Chamonix-Argentière road), bridges may be swept away, high tension lines cut and ski lifts damaged.

Although avalanches have destroyed many alpine holiday chalets, the consequences are more serious when permanent residences are involved (Fig.6.8). On a single day in 1981, Tuesday 20 January, several avalanches in Isère and Savoy engulfed altogether 14 people, two of whom died. Numerous buildings as well as agricultural and touristic equipment were destroyed, including 10 secondary homes in the village of La Morte; 16 houses and the church were damaged in the parish of Clavans. The total damage was estimated at several tens of millions of francs. The death toll can be far more serious if avalanches occur during the high season in a ski resort. In February 1970, 39 people died in a chalet at Val d'Isère, and in the 1988-89 ski season, when there was relatively little snow, 33 accidents were reported involving 105 people, of whom 17 died.

It is among skiers, and more particularly off-piste skiers, that accidents caused by avalanches are most prevalent. The accident at the Aiguille Verte in the Mont Blanc area in July 1964 was undoubtedly the worst of its kind, when 14 victims were killed by a wind-slab avalanche.

7.2. Avalanche protection and prevention

In the past, people's knowledge of danger zones was very fragmentary and often restricted to the immediate vicinity of their traditional village. It was not until the catastrophic avalanches of 1970, and more particularly the Val d'Isère avalanche, that a decision was taken to produce a map of high-risk avalanche sites covering all the mountain systems in France, entitled *La Carte de Localisation Probable des Avalanches* (for example, Fig.6.9). Initially the map, with a restricted circulation, was drawn to a scale of 1:20 000; it will, however, be updated at a scale of 1:25 000.

At parish ("commune") level, the government authorities have funded the production of maps of high-risk avalanche zones for mountain resorts (*Plan des Zones Exposées aux Avalanches*, scale 1:2000 or 1:5000). These are currently integrated into High-Risk Maps (*Plans d'Exposition aux Risques*). All these documents act as guidelines for the zoning of avalanche sectors. Preventive measures are undertaken as follows:

Passive protection: This consists either of taking advantage of the local topography in order to shelter buildings, or of protecting them with wedges, earth-bank deflectors and barriers. Roads may be partially or totally covered.

Active protection: The aim here is to hinder the formation of an avalanche. Snow fences are used as windbreaks for the snow-laden winds, thereby preventing the accumulation of cornices, slabs and other dangerous snow masses. Benches, snow nets and snow rakes are used to improve the adhesion of the snow layer to the ground in avalanche-prone sectors. Afforestation, when possible, is the best solution of all.

Reports on snow conditions; warning systems: The national meteorological office produces an information bulletin that can be accessed by telephone or by Minitel. It reports both on snow conditions and avalanche risks based on an accident-risk probability scale. Ski resorts warn clients of day-to-day conditions, the opening or closing of different sectors of the skiing area, the artificial releasing of avalanches and the systematic clearing of avalanche corridors and slopes as soon as danger threatens. Warning systems stop access to slopes as soon as an avalanche farther uphill is reported.

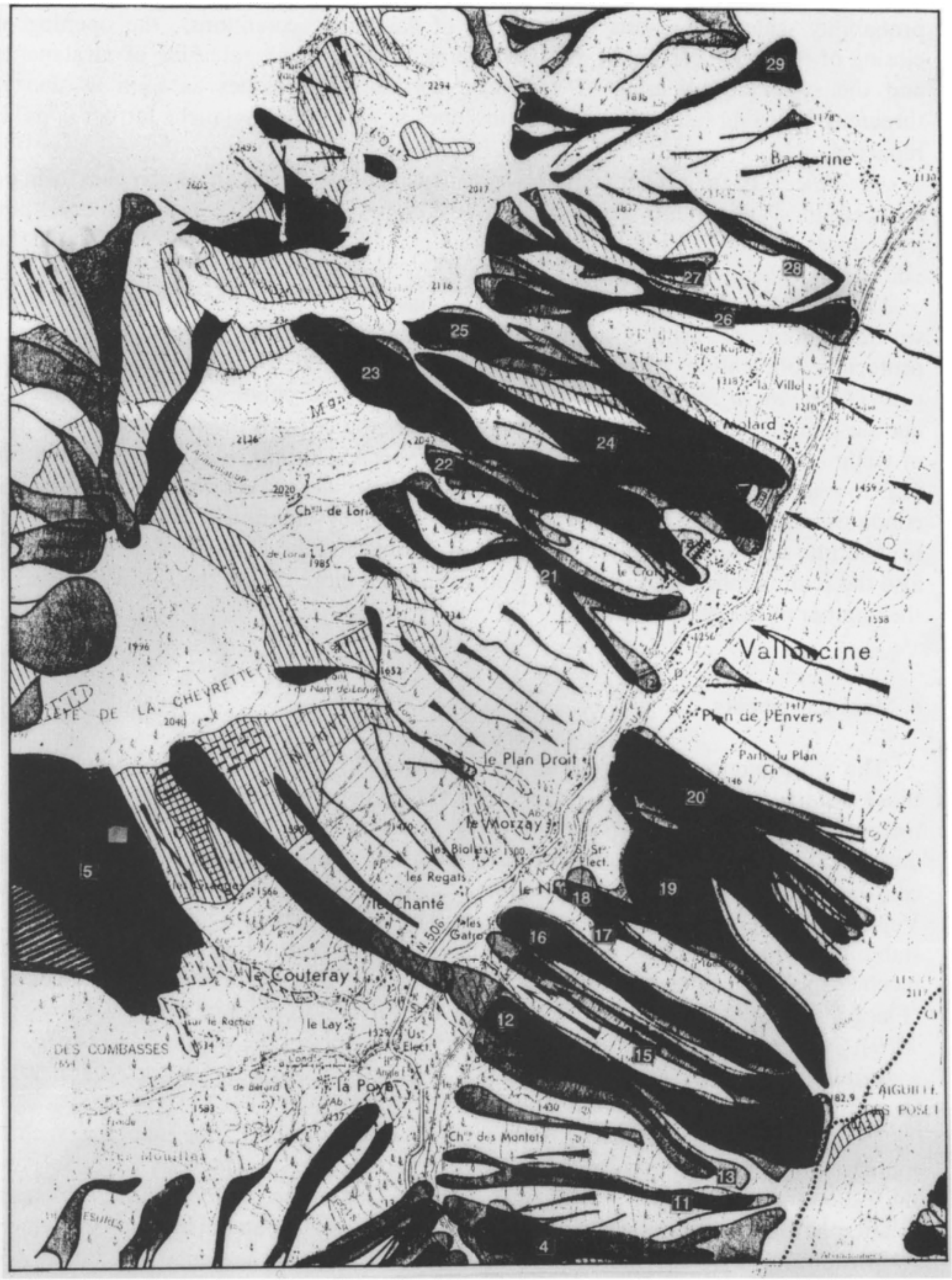
Assistance: There are numerous ways in which the effects of avalanches can be reduced to a minimum. These include the setting-up of search and intervention procedures, victim-location systems, dog training schemes, staff courses and the general education of the public.

Over the last 15 years, all these aspects have been developed in France through various public or private agencies. Coordination, research reports, reviews and protection/prevention initiatives are undertaken by ANENA (*Association Nationale pour l'Etude de la Neige et des Avalanches*), a recognised public service. Nevertheless, and despite all the efforts and progress made over the last two decades, the annual toll of victims has not been arrested. The total number killed fluctuates considerably from year to year (17 killed in 1988-89, 57 in 1980-81) depending on snow and meteorological conditions each winter. In order to obtain a meaningful evaluation, it would be necessary to take into account not only the number of victims and the number of avalanches but also the total number of tourists: this would bring out more clearly the actual increase in the number of lives saved.

8. Mass movements

The more mountainous areas of France, especially the Alps and the Pyrenees, are those where large-scale mass movements, including the debris flows of mountain torrents, are most common (Chardon, 1987; Chardon *et al.*, 1984; Pech, 1988; Soutadé and Becat, 1983-88), but there are also important mass movements on some cliffed coastlines (see section 5.1 and Fig.6.7) and on some escarpments inland (Guérémy and Vejux, 1987; Marre, 1988). Many are triggered by human activities interfering with slope stability, either accidentally or unintentionally. Present research is concentrated on the mechanisms of movement and slope failure, causal factors, prevention and control (Flageollet, 1989; *Mouvements de terrain, 1984; Montagnes fragiles, 1988*; Vié le Sage, 1989). Some centres specialise in this research; for instance, the *Centre de recherches en géographie physique de l'environnement* at the University of Caen has for several years been investigating landslides in Normandy.

Mapping of the phenomena is in progress, including hazard zone mapping, such as the ZERMOS maps (*Cartes des Zones Exposées aux Risques des Mouvements du Sol*) and the PER surveys (*Plans d'Exposition aux Risques*). One of the more difficult problems is to attempt to establish the recurrence intervals for landsliding and other mass movement catastrophes - to determine the probability that an event of particular magnitude will recur in a given time.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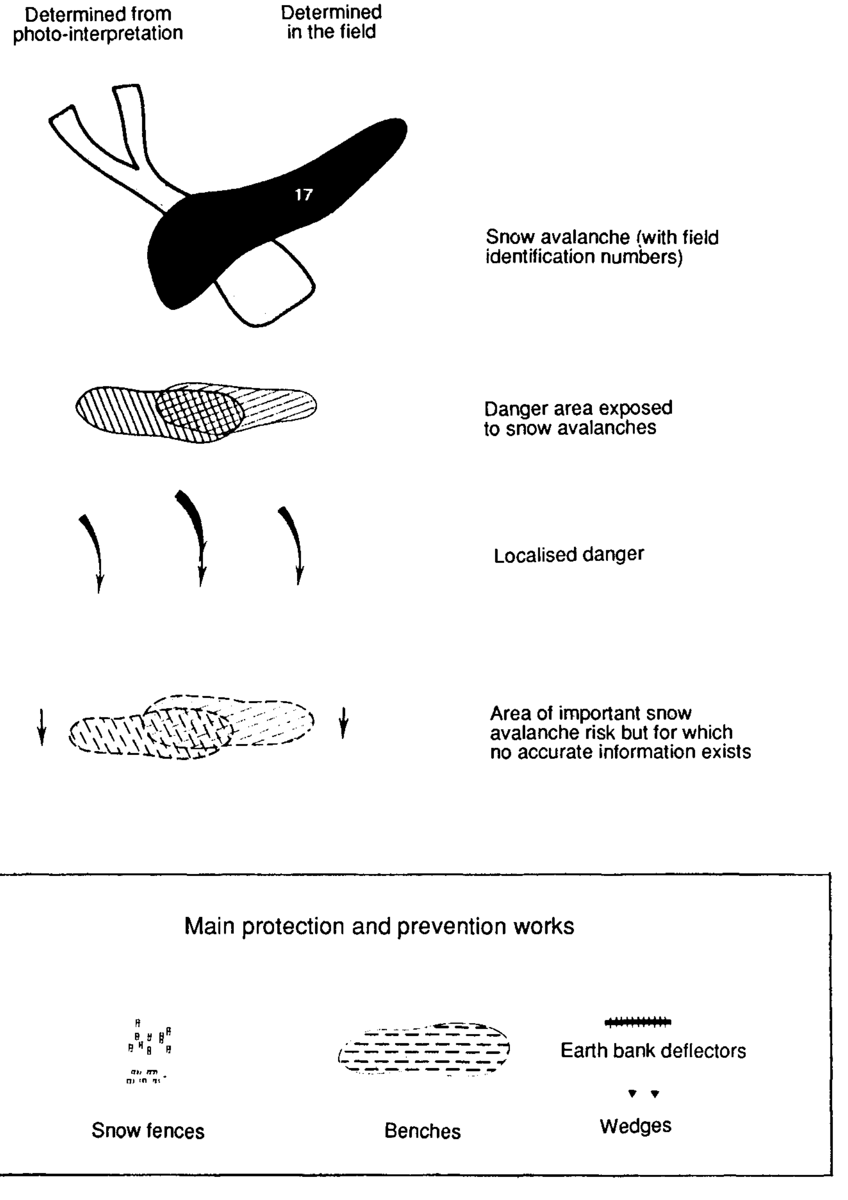

Fig.6.9 Example of the 1:20 000 / 1:25 000 map of high-risk avalanche sites (*Carte de localisation probable des avalanches*)

9. Mass movements associated with earthquakes

Among the indirect effects of earthquakes, mass movements appear as major hazards, not only in areas of high seismicity but also in intra-plate regions where seismic activity is dispersed and generally modest (Cadiot *et al.*, 1979; Humbert, 1987; J.Vogt, 1987b). Four points must be examined in this respect:

1. Rock falls and landslides often exceed the direct effects of earthquakes in terms of property damage and loss of life;
2. These processes are often triggered by events of quite moderate intensity;
3. There is frequently little or no warning of the event;
4. It is very difficult to devise preventive measures since the timing and location of earthquakes cannot be forecast.

It is often difficult to make a confident link between a particular mass movement and an earthquake, especially for older historical events where data are insufficient (*Actes du Colloque*, 1984b; J.Vogt, 1987a, 1988a, 1988b). The French expression "tremblement de terre" (earth tremor) is often used in a broad sense, even recently, to comprise all kinds of ground movements such as collapse or landslides. Likewise, there may be confusion among the results of earthquakes that occurred close together in time (e.g. in 1755 and 1756) and between a mass movement and a remote earthquake (e.g. in French Angoûmois at the same time as the great earthquake in Lisbon). Hence great caution in interpretation is needed.

There is a need for caution even when the earthquake event is clearly recorded. Sometimes an event of modest intensity is enough to trigger ground movement which would not arise in another less favourable geological, geomorphological or meteorological environment. There is no doubt that major earthquakes can induce specific mass movements, but the temptation to infer earthquake occurrence simply from a mass movement event must be resisted. Thus, the famous landslide of Myans in Savoy in the fourteenth century was erroneously attributed to a major earthquake.

Mass movements associated with earthquakes should not, therefore, be separately distinguished, but examined in the course of a broad geotechnical investigation that should also consider previous events that occurred in the absence of an earthquake. It is a pity that some of the earthquake intensity scales have used mass movements as an index of intensity; fortunately, the MSK scale has been revised in the last 15 years. In France, the preparation of ZERMOS maps (see section 8) has allowed reports of possible earthquake-induced hazards and their indirect effects in the Alps and Pyrenees to be included.

There are many data collected during the last 75 years by the French *Bureau central seismologique (Institut de physique du globe*, Strasbourg), and a seismotectonic map of France is being prepared by the *Commisariat à l'Energie Atomique*, starting with a test scheme in the Pyrenees.

In the Pyrenees, mass movements are both numerous and becoming better known (J.Vogt,1984). Movements supposedly associated with earthquakes were often described from the 18th century to recent times, in the border zone between the western and central Pyrenees. It is, however, difficult to establish any link between an earthquake and mass movements that happened some time later. In any case, all scales of activity are present, from an undisputed specific movement to minor movements that followed.

In the Alps, Rothe (1941) investigated the role of seismic disturbances as morphological agents. Numerous observations and descriptions accumulated during the last 200 years are now being reinterpreted (e.g., Julian, 1984). The apparent correlation between earthquakes and meteorological events, as well as the simple application of criteria from formerly adopted MSK scales, urge great caution.

France as a whole is a region of modest seismicity, but mass movements apparently associated with earthquakes are nevertheless numerous. Major events incite many minor adjustments either contemporaneously or a short time later, sometimes out of all proportion to the magnitude of the earthquake involved, and often in the context of predisposing geological and/or meteorological factors. A broad geomorphological and geotechnical approach is essential.

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1. Introduction

Different types of geomorphological hazard in Germany occur with varying frequencies depending on geological, tectonic, relief and climatic conditions. Table 7.1 attempts to record the spatially varying incidence of geomorphological processes that are capable of mobilizing large quantities of debris and that have the potential for causing damage and loss of life. This survey is far from complete, but for the first time it tries to gather together data on geomorphological hazards in Germany and to relate them to the principal landscape complexes.

2. Seismic hazards

Only minor earthquakes have been recorded in Germany and a large part of the country, mainly northern and central Germany, may be classified as aseismic. Leydecker (1986) has published a list of earthquakes that have been recorded historically or instrumentally from the year 1000 to 1981. None is known to have constituted any serious hazard. Another compilation is given by the Federal Survey for Earth Science and Raw Materials (*Bundesanstalt für Geowissenschaften und Rohstoffe*) in 1988.

3. Mass movements and related phenomena

In Germany, mass movements (Fig.7.1) and their related hazards are investigated not only by geomorphologists but also by geologists, forestry and construction engineers. Some of the Federal State Geological Surveys, for instance, are working on the

Table 7.1. Rapid geomorphological hazards: occurrence, importance and frequency

	Alps and the Alpine foreland	Uplands and scarplands *(Mittelgebirge)*	North German lowlands and coasts
Mass movements (including rockfalls, slides and debris flows)	+ + +	+ +	+
Avalanches	+ + +	–	–
Floods	+ +	+ +	+ +
Coastal erosion			+ + +
Karstic hazards	+	+ +	+
Seismic hazards	+	+	+

+ + +	very frequent and important	+	rare
+ +	less frequent and less important	–	insignificant

compilation of registers of these phenomena (e.g. the Geologisches Landesamt Rheinland-Pfalz 1983, 1989) or on the development of mapping systems (e.g. the programme *GEORISK* of the Bavarian Geological Survey: see Poschinger, 1989, and section 3.1). Investigations by the Bavarian forest management service, who have been developing maps of slope stability for forested districts in the Bavarian Alps (Arnold *et al.*, 1985; Laatsch and Grottenthaler, 1972, 1973), should also be mentioned. Many investigations of mass movements are carried out by engineering geologists (Krauter, 1979; Krauter and Steingötter, 1983; Steingötter, 1984; Krauter *et al.*, 1985). In addition, information about mass movements is included on the various 1:25 000 sheets of the Geological Survey.

Geomorphological investigations of mass movements have on the one hand focused on the Alps (including areas outside the Federal German Republic), (e.g. Abele, 1974, 1984; Arnold *et al.*, 1985; Bunza, 1976; Fischer, 1985; Habbe, 1985; Laatsch and Grottenthaler, 1972, 1973; Poschinger, 1989; Strunk, 1986; Veit, 1988; see also section 3.2), and on the other hand in the Central Uplands (Mittelgebirge) and Southern Scarplands (especially on the cuestas and hogbacks) (e.g. Ackermann, 1977; Andres, 1977; Andres and Preuss, 1983; Andres *et al.*, 1983; Bibus, 1985, 1986; Geologisches Landesamt Rheinland-Pfalz, 1983; Krauter and Steingötter, 1983; Krauter *et al.*, 1985; Lehmeier, 1981; Preuss, 1983; Schunke, 1971; Steingötter, 1984). As well as special mass movement investigations, these phenomena are also considered in the context of regional geomorphological analyses. Thus, there is a great deal of information on this theme in the descriptions accompanying almost all the published sheets of the GMK

Fig.7.1. The landslide of Im Laberstall in the Tertiary basin of Mainz, dating from January 1989. Its volume is about 125 000m^3, the height of the scarp about 6-7m (R.Dikau, 1990).

(Geomorphological Map) 1 : 25 000 (Andres and Preuss, 1983; Andres *et al.*, 1983; Fischer, 1985; Habbe, 1985; Lehmeier, 1981), elaborated in the Priority Programme of the German Research Foundation on detailed geomorphological mapping (*Schwerpunktprogramm der Deutschen Forschungsgemeinschaft: Geomorphologische Detailkartierung in der Bundesrepublik Deutschland*): see for instance, Barsch and Stäblein (1989).

Research on mass movement is partly included in the working group investigations of another Priority Programme of the German Research Foundation, namely, that on Fluvial Geomorphodynamics in the Later Quaternary (*Schwerpunktprogramm der Deutschen Forschungsgemeinschaft: Fluviale Geomorphodynamik im Jüngeren Quartär*): see Tables 7.2 and 7.3, and also Ackermann (1977), Andres (1977), Andres and Preuss (1983), Arnold *et al.* (1985), and Barsch and Dikau (1989). These investigations examine not only the dynamics of the hydrological systems, but also the origin of the material transported by rivers.

3.1. The recording and investigation of mass movements in the Bavarian Alps: the project GEORISK (A.v.Poschinger)

The *GEORISK* project was set up by the Bavarian Geological Survey in 1987. Its aim is to collect data on all types of mass movement (except snow avalanches) in the

Table 7.2. Geomorphological investigations in progress or just begun, related to geomorphological hazards and attached to the Priority Programme of the German Research Foundation: *Fluvial geomorphodynamics in the upper Quaternary and Holocene*

Investigators	Subject and locality of investigation	Institution
Barsch/Mäusbacher/ Schukraft/Schulte	Present-day fluvial dynamics in the middle-sized catchment of the Elsenz; Kraichgau near Heidelberg	Univ.Heidelberg (Geogr.Inst.)
Bauer/Moldenhauer/ Nagel/Semmel	Gully erosion and development in forested catchments in the Taunus uplands near Frankfurt	Univ.Frankfurt (Phys.Geogr.Inst.)
Becht/Wetzel/ Wilhelm *et al.*	Sediment discharge in the drainage basin of Lainbach, Bavarian Alps	Univ.München (Geogr.Inst.)
Einsele/Ricken	Erosion, discharge and geomorphological evolution of the Wutach catchment, Black Forest	Univ.Tübingen (Inst.Geologie and Paläontologie)
Ergenzinger/ Schmidt	Dynamics of river bed and coarse bed load transport in the Lainbach basin, Bavarian Alps	F.Univ.Berlin (Phys.Geogr.Inst.)
Garleff/Höfner/ Liebricht	Sediment mobilisation and transfer in the Glatzbach catchment, Alps	Univ.Bamberg (Geogr.Inst.)
Hagedorn *et al.*	Recent fluvial geomorphodynamics and debris flows in Stubaital, Alps	Univ.Würzburg (Geogr.Inst.)
Mäckel *et al.*	Flooding, erosion and sediment discharge in Black Forest catchments near Freiburg	Univ.Freiburg im Breisgau (Phys.Geogr.Inst.)
Molde/Pörtge *et al.*	Erosion and solution in the Wendebach catchment near Göttingen	Univ.Göttingen (Geogr.Inst.)

Note to Table 7.2: Further research is being carried out or planned by various groups unconnected with the Programme above: see Table 7.3 and also Barsch and Flügel (1989), Barsch and Stäblein (1989), Becht (1986, 1989), Bibus (1985, 1986), Brunotte and Sickenberg (1977), Bunza (1976) and Dikau (1988).

Table 7.3. Geomorphological investigations in progress or just begun, related to geomorphological hazards but not to the Priority Programme (Table 7.2)

Investigators	Subject and locality of investigation	Institution
Becht	Erosion and sediment transfer in different catchments from the montane to the alpine-nival zone, Alps	Univ.München (Geogr.Inst.)
Beck/ Fischer	Flooding in the middle Rhine valley	Univ.Koblenz (Geogr.Inst.)
Dikau	Mass movements and predictive models in various regions of the German central uplands and southern scarplands	Univ.Heidelberg (Geogr.Inst.)
Garleff *et al.*	Mass movements: distribution and chronological sequence at the Altenburg, Bamberg	Univ.Bamberg (Geogr.Inst.)
Habbe	Erosion and accumulation in the river Iller, Bavarian alpine foreland	Univ.Erlangen (Geogr.Inst.)
Preuss	Mass movements on cuestas in the south-west German scarplands	Univ.Marburg (Geogr.Inst.)
Schirmer *et al.*	Debris flows near St Vigil, southern Tyrolian Alps	Univ.Düsseldorf (Geol.Inst.)
Stein *et.al.*	Mass movements in various parts of the Alps	Univ.Frankfurt (Phys.Geogr.Inst.)
Sterr	Present-day processes on the German coast	Univ.Kiel (Geogr.Inst.)
Stingl/ Veit	Solifluction, debris flows and fluvial dynamics in the central Austrian Alps	Univ.Bayreuth (Geom.Inst.)
Strunk	Chronological and predictive models of debris flows in the Alps	Univ.Regensburg (Geogr.Inst.)

Note to Table 7.3.: These studies not only aim to understand the factors and conditions but also to date the geomorphological events, in order to establish chronological sequences and predictive models. GIS techniques are employed in many (Barsch and Dikau, 1989; Dikau, 1988, 1989, 1990a, 1990b)

Bavarian Alps, to evaluate the information and to make it available to planners and other users.

Although only a small part of the Alps (c. 3 per cent) falls within the Federal State of Bavaria, the area under investigation nevertheless covers some 4800km^2. For such a relatively large area, it is necessary to adopt a topological, object-related method of recording data, instead of attempting a comprehensive survey. In this way it is possible to deliver results for the whole of the Bavarian Alps at a basic level, and later to increase the level of information step by step.

Although there is plentiful information about mass movements in the area, it is scattered in many different archives, publications and consultancy reports. To build up a "Mass Movement Information System", all of these different sources must be used but it must be borne in mind that the quality of the information will vary and that therefore the sources must always be quoted.

As far as possible, the following data are recorded for each mass movement above a certain minimum size and processed in a ADABAS data bank: location, geology, relief, size, activity, type of movement, degree of hazard, and cause.

Material extracted from the data bank can provide transparent overlay maps indicating the location, extent and direction of movement, the type of movement and the level of activity. As well as these maps, a detailed description of each individual mass movement is compiled; this includes predictions about the further evolution of the slope in question. In this way, planners and other authorities can assess the degree of slope instability and decide, in critical cases, whether further special investigations are merited.

Another function of the data bank is to permit statistical analysis of the slope movements to be undertaken, in order to obtain further insight into the spatial distribution of the movements, and to examine the interrelationships of the causative factors. In turn, the statistical analysis will allow hazard prediction to be improved and ways of mitigating the hazard to be established.

Collecting data on the factors listed above is only one part of the *GEORISK* project. Further details are collected by field investigation. This includes detailed mapping (1:1000 to 1:5000) of selected mass movements and their surroundings, geodetic monitoring and, in special cases, borehole instrumentation.

Experience gained in the study of mass movements in the last few years has endorsed the usefulness of setting up an Information System. As other countries have found, nearly all movements occur in areas where similar events have occurred in the past. This emphasises the need to record not only active movements but also signs of former movements.

There is an urgent need to make information about slope instability easily accessible to planners and decision-makers. This is especially true in respect of construction work in mountainous areas, but must also be seen in the context of probable future climatic change. If some climatological predictions are to be believed, more extreme tendencies in climate are likely to manifest themselves in the near future. Slope equilibrium, adjusted to present conditions, may well have to adjust to meteorological and hydrological changes, as well as to human interference, and many dormant landslides may thus be reactivated.

3.2. Mass movement hazards in the Bavarian Alps (H.Strunk)

Bavaria is the only state of the Federal Republic of Germany to extend into the Alps. Stretching from the Bodensee in the west towards Berchtesgaden in the east, the mountain belt runs for about 260km, with a width of only 10-30km inside German territory; the mountain area is about 4800km^2, or 7.5 per cent of the area of Bavaria (Fig.7.2). Despite their complex geological structure, the German Alps can be differentiated into two main regions. The Pre-Alps strike west-east and are composed of soft Helvetic and flysch rocks (Cretaceous to Palaeogene in age): they are restricted to a narrow belt along the northern Alpine border with a maximum elevation of 1400m. To the south lie the high mountain chains of limestone and dolomite, mainly Triassic in age, and frequently exceeding 2500m, occasionally nearly 3000m in height.

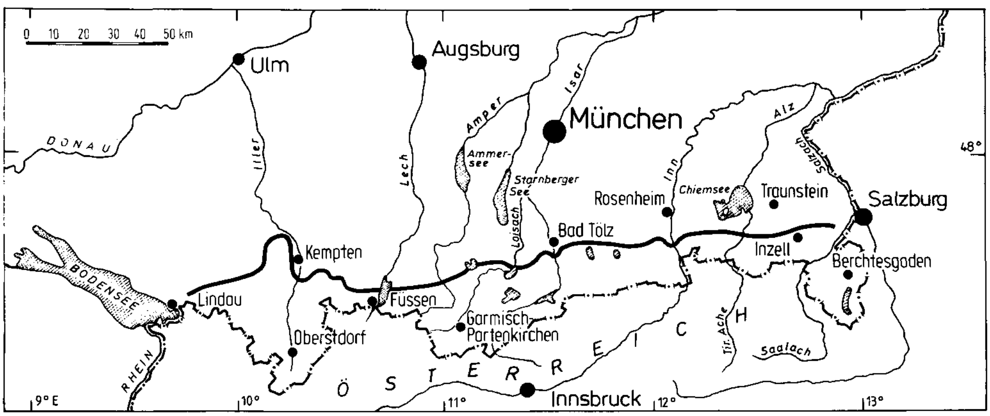

Fig.7.2. The German Alps in Bavaria. The southern border is the boundary with Austria; the northern border is marked by a thick line.

3.2.1. The protective function of mountain forests Nearly 50 per cent of the total area is forested, with a timber-line at approximately 1800m. The important protective function of the forests against natural hazards has priority in law over timber production. Plochmann (1985) estimates that 63% of the forests provide protection against soil erosion and debris flows, 42% against avalanches and 64% against floods: these figures emphasize the importance of their protective function. The spatial distribution of protective forests is documented in maps of the state forest administration, and observance of the relevant regulations by forest owners is strictly controlled by the authorities.

3.2.2. Risk assessment maps of the German Alps A complete and excellent survey of all fossil, inactive and recent mass movements and erosion damage has been published by the Bavarian water management administration in the Hydrographic-Morphological Map of the Bavarian Alps at a scale of 1:25 000 (Bunza and Karl, 1975). By 1988, 43 of the total 53 sheets of the map had already appeared. The map allows geomorphologically unstable zones, as well as zones prone to torrent damage, to be identified, and is fundamental to the work, already started, of restoring and stabilising areas endangered by mass movements and mountain torrents (*Wildbäche*). In addition, the Bavarian forest administration has almost completed mapping of unstable forested slopes in a survey which shows that only 48 per cent of the forested slopes are stable, and that 40 per cent are in a highly unstable condition (Suda, 1989). Finally, the Bavarian water management administration keeps a register of all known avalanche paths, together with a record of the frequency and magnitude of avalanche events.

Although most potential natural hazards are documented by the Hydrographic-Morphological Map referred to above, Germany, unlike Austria and Switzerland, lacks a synthetic map of endangered areas. Such maps have the advantage that they can be immediately understood by politicians and planners, and can help in avoiding the sorts of mistakes in regional planning that can so easily threaten human life and property.

3.2.3. Rockslides and rockfalls Most of the large rockslide and rockfall events occurred at the end of the last glacial period when glacially oversteepened valley slopes became ice free and thus unstable. Huge Late- and Post-glacial landslides occurred at the Hoher Ifen near Oberstdorf where the moving mass amounted to 7 million m^3 (Schmidt-Thome, 1960), on the northern face of the Zugspitze near Garmisch-Partenkirchen (Vidal, 1953), near Marquartstein south of the Chiemsee (Ganss, 1967) and at the Hintersee near Berchtesgaden (Penck and Richter, 1885). These and a number of smaller rockslides have been described in detail by Abele (1974). Historic and recent rockfalls have also been recorded by witnesses. Gümbel (1861), for instance, described an event that had just occurred at Säuling near Füssen, and Leuchs (1921) wrote about a rockfall moving a mass of 50 000m^3 in the Reintal valley near Garmisch-Partenkichen in 1920. In the same area in 1990, a rockfall of more than 10 000m^3 destroyed a footpath leading through the well-known Partnach Gorge. Zankl (1960) reported a rockfall of 350 000m^3 at the Palfelhorn near Berchtesgaden which occurred in 1959, and Karl (1991) described a similar event that occurred in 1963 at Hinterstein near Oberstdorf, when 200 000m^3 of rock collapsed. None of these events caused any loss of life.

3.2.4. Stone and boulder falls Falls of debris such as stones and boulders in many cases originate from bare rock faces. The fragments are loosened by frost weathering during the winter and released in spring when the ice in the joints and fissures begins to melt. On forested slopes, however, nearly 60 percent of the falling stones are stopped by collision with tree trunks (Jahn, 1988). Steep rock slopes where potential stone and boulder falls are likely to endanger important road links are cleared of loose rock fragments each spring, as for example on the slopes of the Weißbach gorge leading down to the main road 305 between Inzell and Berchtesgaden. Significant damage by rock and boulder falls is therefore extremely rare.

3.2.5. Rotational slides and mudslides The intercalated marl and clay horizons within the Mesozoic carbonate rocks, and especially the slopes of the Pre-Alps composed of flysch and molasse marls and clays, are particularly susceptible to sliding. The instability of these slopes has long been known to the local population who have avoided settling there. Instead, the slopes are covered with mixed forest which, by promoting interception, evaporation of surplus soil water, and by deep root systems, helps to stabilise the slopes. Nevertheless, mass movements occur from time to time, as for example in spring 1991, when a huge mudslide endangered nearly all the new holiday chalets of a village near Inzell.

3.2.6. Debris flows As a result of the continuous fight against torrent (*Wildbach*) hazards by torrent control measures and the encouragement of natural slope protection for over a hundred years by the water management administration, debris flows in the German Alps are now a rare phenomenon. In the tributary catchments on the northern border of the Alps, however, unconsolidated Pleistocene glaciofluvial sediments (interstratified gravels, sands and silts) up to 200m thick in places are permanently at risk from debris flow development (Becht, 1989; Becht and Kopp, 1988). Here the heavy convection rain and hail of summer thunderstorms are especially effective in causing deep erosion in torrent headwaters, leading to rotational slips and debris flows.

The magnitude of extreme daily precipitation amounts rises from the north towards the south-east in the German Alps. The probable recurrence interval of daily rainfall amounts of 50-80mm, which may set off debris flows, is only one year. Daily rainfall of 80-120mm is likely to occur every 10 years, while the probable recurrence interval of 120-200mm falls is 100 years (Deisenhofer, 1984). Becht (1991) measured 90mm in one hour in the northern Pre-Alps, with no less than 51.7mm falling in one interval of 15 minutes. Even these values are dwarfed by the 122mm which fell in just 8 minutes near Füssen. As the rainfall intensity increases, so does the probability of occurrence of debris flows; where there are great thicknesses of loose material, there is an almost permanent risk.

3.2.7. Avalanches In the German Alps, 42 per cent of the forested area, or 100 000ha, serve as protective forest against avalanches (Plochmann, 1985). This function of forests was recognised and embodied in the Bavarian Forest Law of 1852 (Suda, 1989). The Register of Avalanches kept by the water management administration facilitates monitoring of the avalanche paths that endanger settlements and thoroughfares, and enables the authorities to take carefully directed precautions in terms of temporary or permanent avalanche control.

3.2.8. Floods The summer half-year in the Central European climatic zone is often characterised by high-intensity convection rainfall. As the convection cells are usually small, only local drainage areas are normally affected by an individual event. The risks presented by longer-lasting advection rainfall, or by rapid snowmelt, are considerably reduced by the water-retaining capacity of the large wooded areas. By interception, infiltration into the loose forest soil or snow cover, and throughflow in talus or snow, runoff is retarded to the extent that peak discharges in the rivers are also reduced. The numerous natural lakes and bogs also help in this. In addition, the lower Lech valley is protected from floods by the large Forggensee reservoir near Füssen.

3.2.9. Future trends of geomorphological hazards The forest die-back syndrome largely caused by air pollution reached the German Alps in 1981. The area of mountain forest afflicted, less than 2 per cent in 1982, already totalled 38 per cent in 1983 and reached 53 per cent by 1985 (Mössmer, 1986). The high proportion of visibly affected spruce trees (the major species of the sub-alpine forest), whose main function is to protect against rapid mass movement hazards, is alarming. Kennel and Reitter (1986) have stated that, already in 1985, 75 percent of spruce trees more than 60 years old, were visibly affected. From 1983 to 1985, the proportion of forested areas with strongly affected or dead trees increased by a factor of six, equivalent to 13.2 per cent of the total wooded area (Suda, 1989). Forests with one or more protective functions against geomorphological hazards are equally affected by forest decline. So far, there is no sign of mountain forest recovery in the annual oscillations of amounts of forest damage.

The urgent need for natural regeneration of the forest stands is further hindered by the damage caused by browsing animals such as roe deer, red deer and chamois (Liss, 1988). This is the result of too great a game population in the German Alps, which has multiplied by a factor of 3.6 from 1861 to 1968 (Plochmann, 1985). Even the young trees, planted by hand at high cost as part of the restoration programme of the Bavarian government (Schreyer, 1987), are being damaged (Schauer, 1987). A drastic reduction in the game population, the only possible solution, is doomed to failure because of opposition from the hunting lobby, which exerts great political influence in Bavaria.

Faced with these dramatic forest changes and damage, many workers (e.g. Ammer, 1986; Ammer *et al.*, 1985; Jobst and Karl, 1985; Karl, 1985; Suda, 1989) have already been warning of the severe consequences that these developments may have, namely, more and more flood catastrophes on the mountain torrents, debris flows and slides on unstable slopes, avalanches and rock falls. It is even possible that whole valleys may become uninhabitable and impassable. The rapid increase in numbers of forest-area avalanches (Zenke, 1985), eight of which have since 1987 afflicted German alpine roads that were formerly known to be free of avalanche risk (Zenke and Konetschny, 1988), confirms these fears.

4. Hazards related to karst processes

Geomorphological hazards related to karst processes, underground solution and collapse of subterranean caves (Fig.7.3) are particularly associated with areas of soluble

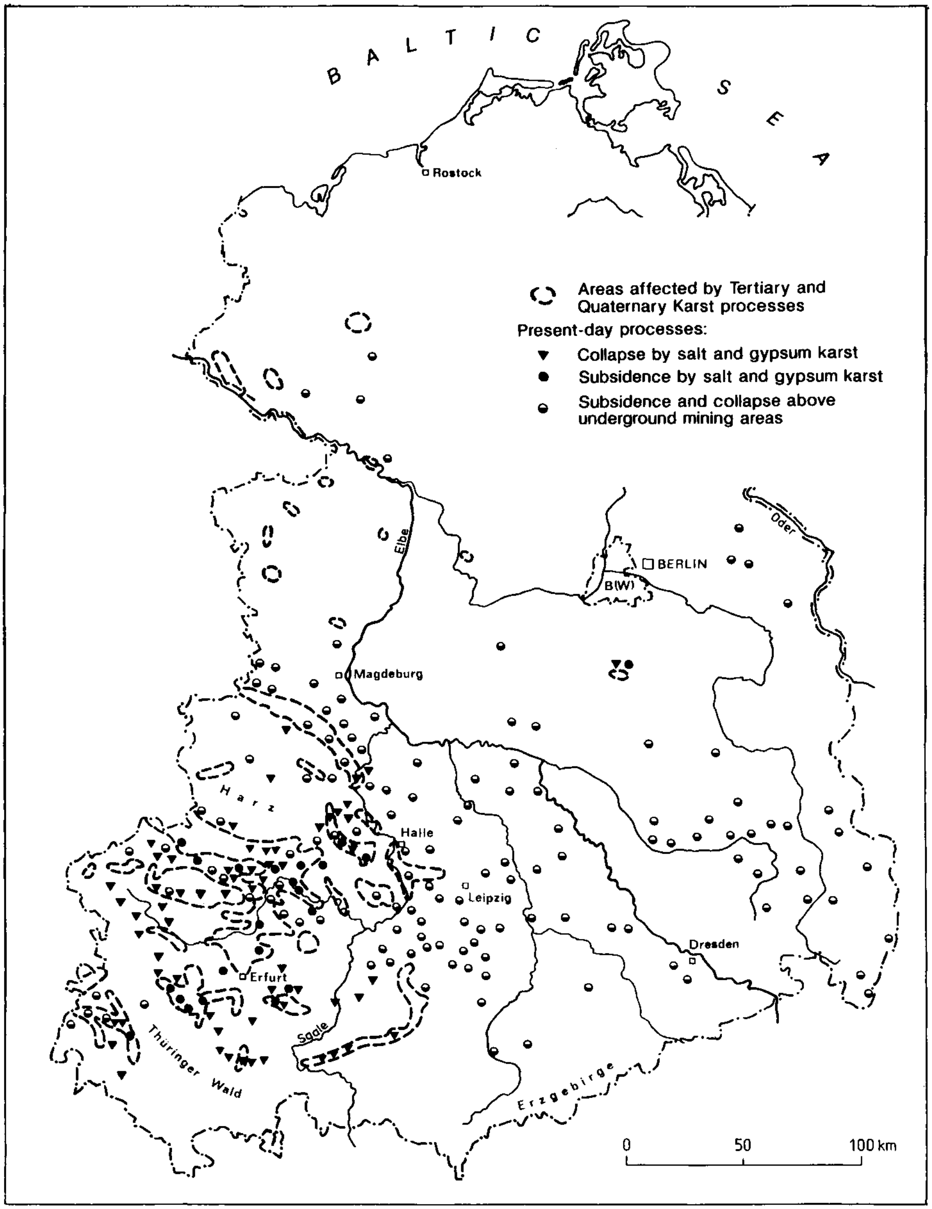

Fig.7.3. Karstic hazards in eastern Germany

sulphate and chloritic rocks, but less so with calcareous rocks (mineral and potash salts, gypsum, anhydrite and limestone). The soluble formations of the first group occur frequently in strata of Upper Permian age, less frequently in the Triassic platform sediments. Permo-Triassic rocks come near to the surface or outcrop around the Harz mountains and along the fringes of other central German uplands (*Mittelgebirge*) in Hessen, Niedersachsen and Thüringen, and also at a few places in the north German lowlands where diapiric structures of Permian evaporites lie at relatively shallow depths, 300-500m below the surface. Jurassic and Cretaceous limestones with carbonate karst are more widely distributed in the southern and western parts of the Mittelgebirge.

Hazards caused by underground solution or other sub-surface karst processes have been extensively studied by geologists, especially in connection with engineering construction such as railways, bridges and motorways (e.g. Baule and Dresen, 1973; Drescher and Jordan, 1973; Dreyer, 1973; Habetha, 1972; Herrmann, 1972; Jordan, 1986; Laemmlen *et al.*, 1979; Meiburg, 1980; Prinz *et al.*, 1973). In eastern Germany there have been similar investigations, for instance by Kugler and Villwock (1990). There is also much information on this topic in the descriptions accompanying the various maps of the geological survey and the 1:25 000 geomorphological maps. Recent research on underground solution and karst processes by geomorphologists includes studies by Brunotte and Sickenberg (1977), Friedrich (1985), Kugler and Villwock (1990), Möller (1988), Priesnitz (1970, 1974), Simon (1980), Stäblein and Möller (1986).

The evaporites are important industrial raw materials, and areas in which they are exploited have developed substantial industries, settlements and a communication infrastructure, all vulnerable to subsidence. Natural karst processes, which seem to have been more active in the early Tertiary and late Pleistocene, actually show only weak effects, but on the other hand, the effects of mining engineering, copper and salt mining, and water pumping have been to intensify and modify these natural processes.

The relief forms generated in this way by human interference closely correspond to those of natural karst. The principal ones are subsidence troughs and basins produced by slow surface deformation without fractures, and sinkholes or shafts produced by rapid spontaneous collapse. The features present a wide variety of sizes: the diameters of collapses range from less than 2m to more than 100m, while subsident areas can cover up to $10km^2$. Measurements of rates of subsidence show values of 20-200mm per year in an area of underground mining west of Halle (Suderlau *et al.*, 1972). The processes frequently cause considerable damage to buildings and transport facilities, and also to arable land where waterlogged areas develop.

Other types of subsidence and collapse are related to ore mining and abandoned brown coal workings, which also give rise to local problems and restrictions for land use.

5. Coast erosion, soil erosion and floods: general introduction

Coastal erosion, floods and avalanches were investigated in Germany in previous decades mainly by technicians and scientists working in disciplines close to but outside geomorphology. In the first place, floods and avalanches are the province of hydraulic engineers and related authorities. Information about coastal floods and coastal erosion is collected by the geological surveys of the north German Federal States, especially in Niedersachsen, Hamburg, Schleswig-Holstein and Mecklenburg-Vorpommern, and by other regional authorities concerned with hydrology and coastal protection, for example the Leichtweis-Institut and the Franzius-Institut in Hannover, which issue special publications in these fields.

Geomorphologists from universities in north Germany have been active in coast erosion investigations (Sterr, 1985; Sterr and Boedecker, 1987, 1989; see also sections 3.1 and 3.2). Process work on river flooding and related phenomena is being undertaken by sub-groups of the Priority Programme on fluvial geomorphodynamics (Table 7.2; see also Barsch and Flügel, 1988, 1989; Becht, 1986; Felix *et al.*, 1985, 1988; Pörtge, 1986; Pörtge and Hagedorn, 1989; Wagner, 1987). In addition, there are some new investigations just starting in this field (Table 7.3).

Some important trends of research into the flood hazard are the investigation of temporal sequences in fluvial dynamic phases, and the relationship of fluvial dynamics with other geomorphological processes (e.g. various types of mass movement) in river basins (Barsch and Flügel, 1988, 1989; Becht, 1986, 1989; Felix *et al.*, 1985, 1988; Veit, 1988). The research aims at understanding the conditions controlling these processes, and the differences in methodology, problems, processes and results corresponding to the different scales of the morphodynamic systems.

In the case of the new Federal Provinces of east Germany, the first summary of those present-day geomorphological processes that are potentially hazardous with respect to land utilisation and development capacity (soil erosion, coastal erosion, zones liable to mass movement, karstic collapse and mining subsidence) was published in map 2 of the Atlas of the former DDR (Gotha/Leipzig, 1977).

5.1. Coastal hazards on the North Sea and Baltic coasts (H.Sterr)

The nature and origin of geomorphological hazards on these coasts can be related to the external oceanographic and meteorological controls, the regional variations in lithology and exposure and the marine and other processes at work along the shore. The external controls comprise the present net rise in sea level affecting these coasts, the influence of tides, currents and storm surges (note that the Baltic Sea is virtually tideless), the presence of winter sea ice in the Baltic, and the incidence of strong onshore winds governing wave energy. Lithological variations reflect the variety of glacial, glaciofluvial and post-glacial sediments dominating these coasts. The most exposed units are the wave-exposed foreshore areas and shoals, exposed island and mainland beaches, the wadden (tidal or salt marsh) areas near to large tidal channels, the wadden rims, cliffs (varying in degree of exposure and height), and exposed dunes (especially those lacking in significant vegetation). Among the processes at work are wave abrasion (on the foreshore and at the cliff foot), sediment transport (both off-shore and along-shore), erosion of tidal channels, shoreline abrasion by drifting ice, slope

failure on cliffs, and wind blow-outs on sandy areas. The principal hazards that result comprise the following:
1. Lowering of the foreshore profile
2. Erosion of the tidal marshes; overdeepening and headward erosion of creeks
3. Lowering of beach profiles
4. Rapid basal cliff retreat
5. Mass failure and slumping on the cliff slopes
6. Dune erosion and migration

In addition to the spatial differentiation of the various processes, their operation through time must also be considered: long-term rates of shoreline, cliff or channel erosion as against the short-term effects of extreme events.

Four examples will now be given, representative of the following environments (Fig.7.4):
1. The tidal flats of north Frisia; rapid erosion of a tidal channel at Norderhever
2. The west coast of Sylt island; cliff, beach and dune erosion; foreshore erosion caused by storms and storm surges
3. Late-glacial moraine cliffs in the southern Kiel Bight; cliff erosion and retreat, slope processes
4. The Fischland sandy cliff and spit area, Mecklenburg-Vorpommern; general problems of cliff, beach and foreshore erosion, and dune blow-outs.

5.1.1 The Norderhever tidal inlet, North Sea coast The area of the Wadden sea in north Germany developed its present hydrology and morphology over the last 600-800 years, when a formerly marshy coast became inundated as a result of land subsidence, sea-level rise, increasing tidal range and storm-related flooding (Bantelmann, 1966; Ehlers, 1988). Along with its transformation into a eulittoral zone, the major drainage systems of tidal inlets began to develop within this area of tidal flats, and the reorganisation of these drainage patterns is still in progress. Tidal channel courses and profiles, through which the major exchange of water and sediments takes place during tidal cycles, are subject to morphological changes, often rapid, that appear to be closely related to the volumetric characteristics of subsidiary channel drainage areas and to prevailing tidal current conditions (MELF, 1981). During storm surge conditions, current velocities can reach four to five times their average speeds. Thus, tidal streams affected by storm surges, which may set up the high tide level by more than 4m, are capable of rapid lateral and headward erosion of their channels. These processes locally result in massive sediment export from the surface and edges of tidal flat drainage basins (Reineck, 1978; Rohde, 1984).

A detailed study of the hydro-morphological patterns within two drainage basins in this area (MELF, 1981) showed that they have not been in a state of equilibrium for a long time. The Norderhever drainage basin, located between the islands of Pellworm and Nordstrand (Fig.7.4), with its tributary channels of Holmer Fähre and Butterloch currently suffers from an extreme lack of sediment (approximately 50 million m^3) according to calculations on the balance between drainage area and channel transport capacity. Because of this, the Norderhever tidal channel has deepened its cross-profile from 2.3m in 1633 to 23.3m in 1976, while at the same time increasing its width tenfold (Fig.7.5). Both of the side channels have considerably extended their catchments by headward erosion in recent years and have begun to undercut the wadden basement of the adjacent island and mainland coast. In addition, a formerly minor channel connecting the Norderhever with the Süderau inlet has markedly increased in width and depth, and is now transporting large volumes of water and sediment into the neighbouring drainage basin to the north.

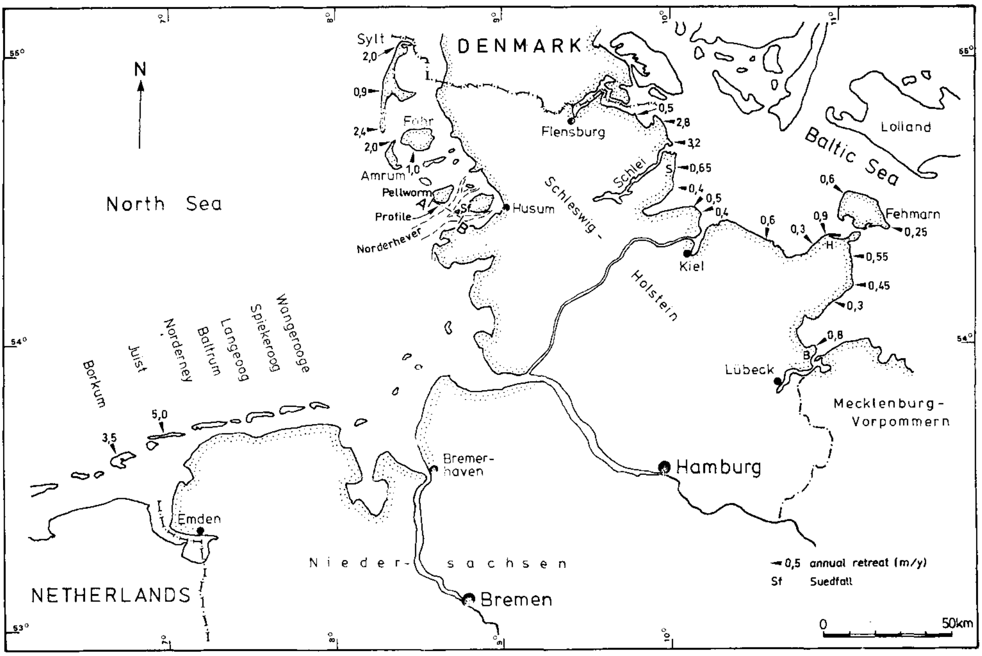

Fig.7.4. The North Sea coast and the western part of the Baltic Sea coast in Germany, showing localities mentioned in the text, amounts of annual coastal retreat and segments with shoreline protection. Three of the study sites are shown by initial letters: B: Brodten cliff, H: Heiligenhafen cliff, S: Schönhagen cliff

These alarming erosional trends appear to be related to increases in the frequency and magnitude of storm surges observed during recent decades, which are accompanied and magnified by secular sea-level rise and increasing tidal range in the German Bight (Führböter, 1986). According to the latest assessments, the sediment deficits and erosional trends were even further intensified by the sequence of three strong storm surges in January and February 1990.

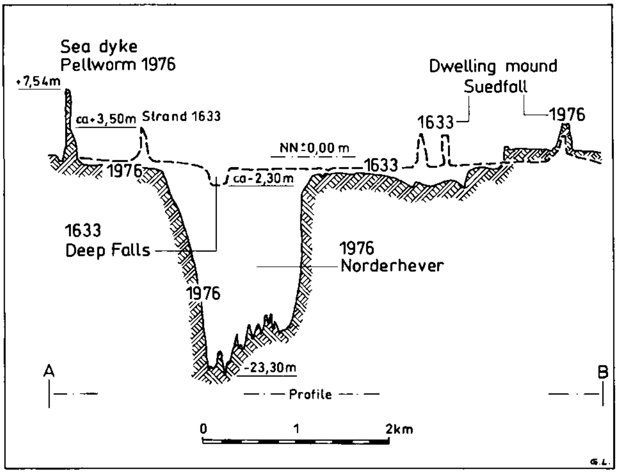

Fig.7.5. Cross-section of the Norderhever tidal channel (for location see Fig.7.4), showing the overdeepening that took place between 1633 and 1976. NN: Normal Null, or mean sea level today

5.1.2 The island of Sylt (Fig.7.6) The North Sea coast, lying less than 5m above mean sea level, is a meso-tidal environment (tidal range 2-3m) which is sporadically exposed to disastrous storm surges that may set up water levels more than 4m above mean high tide level. During such storms wave heights > 6m at the coast are not uncommon and heights > 8m have been recorded (Führböter, 1974). Compared with the migrating East Frisian islands, which were built from marine sand in the late Holocene, the North Frisian islands consist of glacial till and outwash deposits and are thus stable in position. Owing to a westerly exposure and considerable fetch (more than 200km), wave attack causes considerable erosion of their western seaboard. Shoreline retreat is enhanced by north-south moving currents which, by depositing eroded sediments into the deep tidal channels, lead to a permanently negative sedimentary balance along these coasts.

Because of its size, shape and location Sylt serves as a "wave-breaker" for a large area of the wadden and the mainland coast lying farther east (Fig.7.4). Erosion on Sylt's western flank is most obvious along the so-called Red Cliff (built of yellowish-brown glacial till) that extends for about 6km between Wenningstedt and Kampen. To the south, the till cliff is covered by dune sand and, at central Westerland, is partly protected by a sea wall, revetment and tetrapods. The long-term rate of retreat of the unprotected cliff in central Sylt was about 0.8m per year up to 1952, but since then it has increased to 1.5m per year (Dette and Gärtner, 1987). During three storm surges in January 1976 the cliff retreated a total of 5-7m and in 1981 retreat of 9m occurred in just one storm. Similar rates were noted during the gales of January and February 1990, in spite of massive beach feeding at the cliff base.

Several unfavourable factors seem to be responsible:
1. Soft material (kaolinite sand) underlies the till core, facilitating erosion and steepening the offshore slope. Comparison between old and new sea charts shows that the -10m isobath has been migrating rapidly eastward in recent decades (Köster, 1974), faster than the rate of shoreline retreat.
2. In the general north-south trend of the coastline there is a 20-degree change of alignment near the centre of the island (Fig.7.6); this knick favours export of sediment from this part both to the north and to the south at all times when winds blow from the west, thus causing a strongly negative sediment balance there (Lamprecht, 1955).
3. According to Führböter (1976), storm surges have noticeably increased in frequency, height and duration along this coast in recent years; as a result, incident wave energies and current velocities in the foreshore zone are generally higher along the western flank, while the increase seems most pronounced around the ends of the island. Here the wind-induced processes are strongly overlain by gradual changes in the course and depth of the large channels - Lister Tief and Hörnum Tief - which separate Sylt from the neighbouring islands.

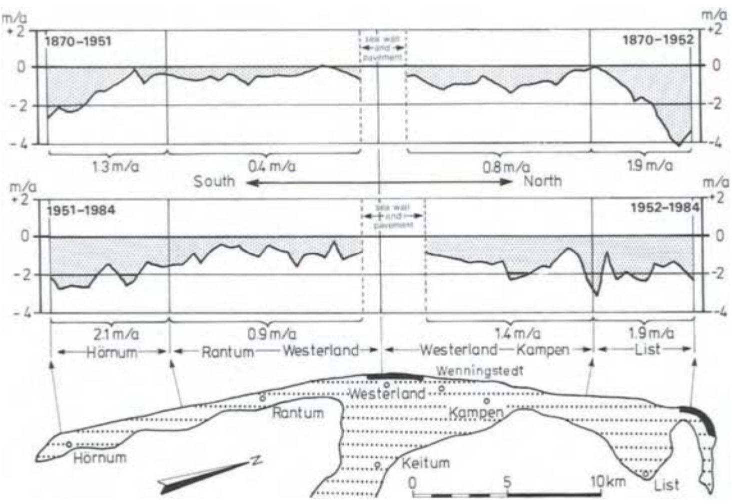

Fig.7.6. Coastal erosion rates along the west flank of Sylt island in the periods 1870-1951/52 and between 1951/52 and 1984. The lower part of the diagram shows a map of Sylt overall.

It is this latter factor that is largely responsible for the rapid shoreline retreat and sediment losses at the northern and southern extremities of Sylt (Fig.7.6). Even more so than in the central part of the west coast, erosion has become critical at the recurved spit in the north (Ellenbogen) and, in particular, at Hörnum Odde in the south (Fig.7.7). Although the reshaping of the coast there is mainly due to natural conditions (especially the deepening and migration of adjacent tidal inlets), it has been strongly enhanced by the construction of a tetrapod wall and groyne south-west of Hörnum in 1962. South (leeward) of these structures, beach and dune erosion has almost doubled in the years since their construction: since 1984, the erosion loss has been more than 10m. Losses of material at Hörnum Odde are estimated to be between 350 000 and 500 000m^3 per year, and thus account for about one-third of the total yearly sediment lost from Sylt (Newig, 1981). Since the last official shoreline mapping and analysis (MELF, 1986), conditions have become even worse, and 1990 saw a break-through across the dunes at the southern tip of the peninsula.

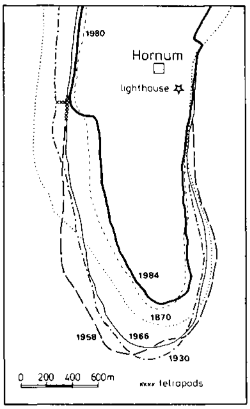

Fig.7.7. The southern end of the Sylt island peninsula, showing the considerable eastward shore-line migration and erosion between 1870 and 1984

5.1.3 The till cliffs of the western Baltic Sea coast The east or Baltic coast of Germany (Fig.7.8) may be characterised as a fjord-and-bay (Föhrde) coast in the west and an estuarine-type (Bodden) coast in the east, though all parts were affected by glaciation in the Pleistocene and are predominantly built from glacial deposits. Prior to 5000 BP, the outline of the coast was very irregular, promontories alternating with bay beaches, but in late Holocene to historic times, shoreline smoothing has been very effective. This was the result primarily of longshore drift in which material eroded from the cliff segments is transported to the adjacent bay beaches, inlets and so-called "fjords". Tides in the Baltic Sea are negligible (less than 20cm); waves and breakers are responsible for abrasion of nearshore platforms and the bases of cliffs and, together with wave-induced currents, move sediments longshore and offshore.

The most important factors governing local process patterns are:

1. The length of fetch normal to the shore, which affects incoming wave power, the direction of dominant wave approach and thus the magnitude and direction of net sediment transport.
2. The range of water-level set-up during storms and the frequency of storms. Marked changes of water level occur in the range between +3.5m and -1.5m, easterly winds raising the water level along most sections of coast and westerly winds lowering it (Sterr, 1988).
3. The volume of the beach prism and thus the height of the cliff base above mean sea

level; both are closely related to the incoming wave energies at each particular coastal segment (Sterr and Gurwell, 1991). Cliff bases lying at less than 1.5m above mean sea level are reached much more often by wave run-up than those above this level.

4. The site-specific stratigraphy of the cliff lithology in which clay-rich strata are responsible for the initiation of widespread slumping, sliding and creep on the cliff face.

The long-term trend of coastline retreat and smoothing is enhanced by a steepening of the shore-normal profile plus a landward migration of the breaker zone (Kannenberg, 1956; Sterr, 1988). Such a trend appears to be linked both to the accelerating rise of relative sea level (presently more than 2.5mm per year) and to a recent increase in the frequency of storms.

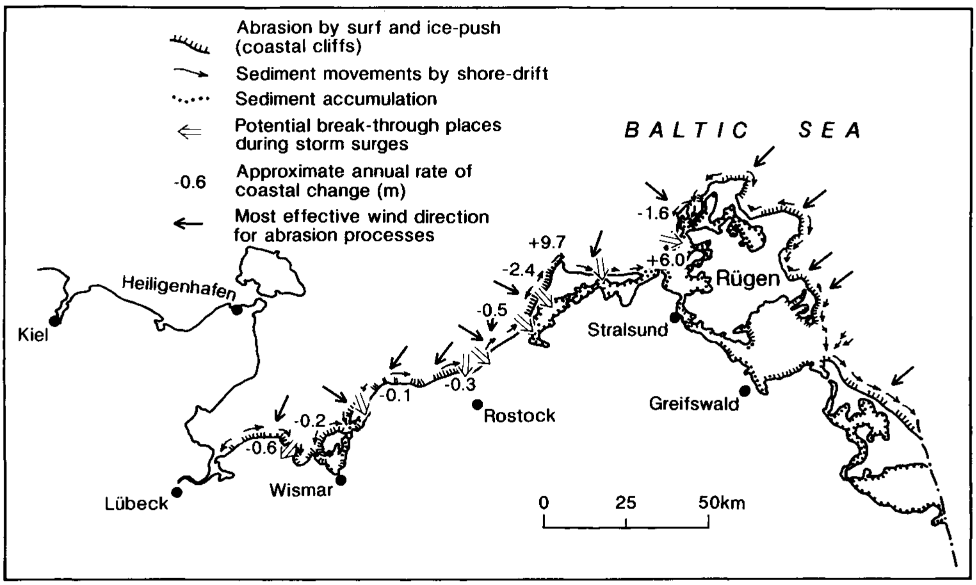

Fig.7.8. The Baltic coast of Germany

The cliff of Brodten with its convex profile is a representative example of cliff development on the Baltic coast. Situated at the mouth of the Trave river north-east of Lübeck (Fig.7.4, letter B), it is exposed to a fetch of more than 100km in a north-easterly direction. According to Petersen (1952) and Kannenberg (1951), the maximum rates of retreat are approximately 1m per year in the central portion between 1875 and 1950. Comparison of a more recent survey (1953-1978) with the older maps reveals that average retreat rates over the whole cliff length (4km) have increased slightly from 43cm per year to 55cm per year but that maximum rates do not appear to have changed significantly between 1953 and 1978 (80-100cm per year). This erosional intensity renders the Brodten section one of the few cliffs on the Baltic coast where retreat is of the same order as that at the Red Cliff on Sylt. Such high rates are, at this site, mainly the result of extraordinary wave energies arriving at a low beach profile, with wave heights occasionally greater than 4m during north-easterly storms. The latter often coincide with water-level set-ups of over 1m above mean sea level.

The cliff and spit at Heiligenhafen (Fig.7.4, letter H) has a convex outline exposed to the west and north, and thus to frequent wave attack from this quadrant, while the effects of water-level set-up remain relatively small. Sediments derived from the abrasion of a till cliff 2km long and 6-11m high drift eastward and have formed a spit 2.5km long, with a series of well-developed beach ridges. Both cliff and spit are eroded by waves coming from the west and north. As the spit, originally orientated north-east to south-west, retreats much faster than the adjacent cliff, the shoreline convexity and its susceptibility to erosion have become more and more pronounced. The increase in the rate of coastal retreat along the spit east of the cliff has become critical with the construction of a groyne, intended to provide a recreational beach, resulting in enhanced erosion on its leeward side. On the windward side of the groyne (to the south-west), a considerable increase in cliff retreat has been recorded. Since Kannenberg (1951) reported retreat of 30cm per year, the rate has subsequently tripled (95cm per year between 1951 and 1980 at the eastern end of the cliff). Along with the increasing rate of sea-level rise and/or storm-wave run-up, mass movements on the slope face, especially rotational slides related to high-density clays within the till sequence, are responsible for sporadic large-scale cliff retreat. Abrasion and steepening of the foreshore slope are contributing to increased wave-base attack at Heiligenhafen, as well as at Schönhagen to be considered next.

The cliff at Schönhagen lying 5km south of Schlei Fjord and exposed due east, is 1.5km in length and, according to three comparative surveys, has the highest average retreat rates of all the western Baltic cliff sections (Fig.7.4, letter S). According to Kannenberg (1951), former erosion rates were about 50cm per year for the whole headland, with shorter segments reaching 85cm per year. Between 1960 and 1986, the average retreat for the whole cliff increased to 65cm per year (Sterr, 1988), while recently, during a major storm in January 1987, no less than 5m of cliff disappeared (Sterr, 1989). The submarine profile of this cliff section has been found to be the steepest in Kiel Bay (Klug *et al.*, 1989) and, unlike most other cliffs, there are no nearshore sand-bars off the coast at Schönhagen. Because of the low beach, breakers reach the cliff foot during water-level set-ups of 0.5m or more, which occurs at least ten times during "normal" years. In the absence of significant lithological weaknesses in the structure of this cliff, its rapid erosion must be a direct function of wave-induced processes, in particular, wave attack at the cliff base during times of slight water-level set-up associated with easterly winds.

The cliff and spit at Fischland receive the highest wave-energy inputs of the Baltic coast west of Rügen island (Fig.7.8). The Fischland peninsula comprises a cliff 3.1km long facing north-west and consisting mainly of unconsolidated sandy outwash. Fed by sediments from cliff abrasion, narrow spits extend from each end of the cliff, north-eastwards and south-westwards respectively. As the peninsula is only a few hundred metres wide near the ends of the cliff, consisting of dune-covered beach ridges, a severe storm could cause break-throughs, creating new inlets connecting with the Saaler Bodden. The long-term abrasion rate for the cliff amounts to 46cm per year, averaged over 100 years, compared with an average of 34cm per year for other eroding coastlines in the southern Baltic. At Fischland (Fig.7.9), the mean value varies along the cliff rising to nearly 80cm per year towards the northern end. However, during the last observation period, 1982-86, the average retreat rate was more than three times higher than in the first phase of records, 1885-1903. For 1978-82, Gurwell (1985) even reported a maximum retreat rate of 1.85m per year, in sharp contrast to the mean of 25cm per year for the previous 11 years. Unlike other sites, the greatest rates of retreat occur where the cliff is composed of fairly compact glacial till and reaches its greatest heights. This suggests that wave undercutting and lowering of the beach/foreshore profile are the main controls, whereas mass movements are of minor importance. It appears that, in

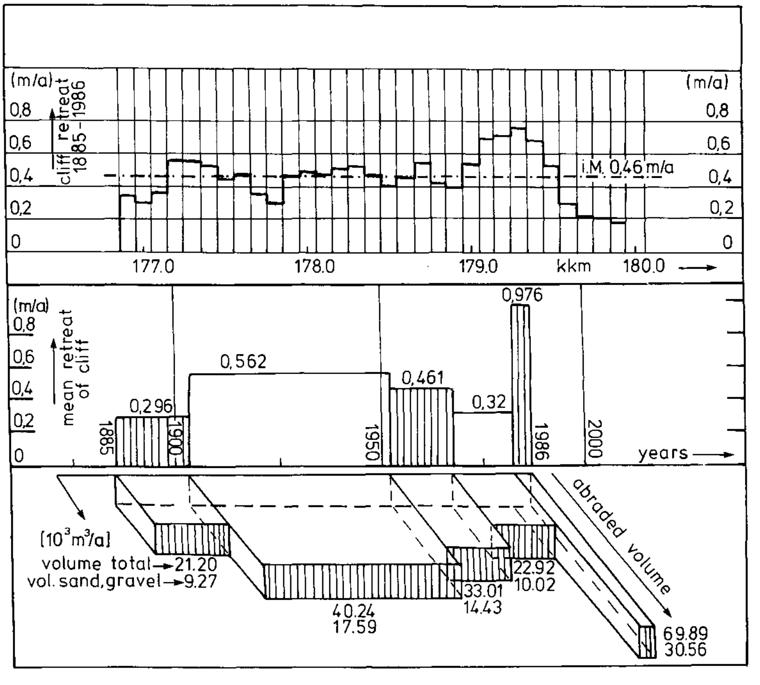

Fig.7.9. Cliff retreat at Fischland, showing long-term mean erosion rates in the period 1885-1986 for the 1km-long cliff segment (top), the time-dependent increase in retreat rates within selected periods (middle) and the volumes of abraded cliff material (bottom).

order to sustain continuing or even accelerating wave attack, the whole coast has been undergoing parallel retreat, which also involves lowering of the nearshore abrasion platform down to a critical depth, which along this coast was taken to be -10m (Gurwell, 1985). From the variations in erosion along this section, it seems that the observed cyclic retreat of cliff and shore depends on the amount of mobile sediment in the nearshore zone. This in turn is primarily a function of the frequency of storms which along this segment produce significant breaker heights (>1.5m) but only a minor water-level set-up. A local peculiarity at Fischland is the effect of wind corrasion and blow-out on those parts of the cliff with a very high sand content. The deflationary action of frequent strong onshore winds blowing across the cliff largely replaces the slopewash, creep and slide processes associated with more coherent cliff lithologies. The wind action results in the formation of cliff-top dunes which in turn are either eroded or incorporated into the overall retreat of the cliff face through over-steepening from below and slope failure. Similarly, the dune systems covering the spits on either side of the central cliff portion are also subject to intermittent major blow-outs. The resulting dune hollows may then at times of storm surges provide routeways for the further penetration of waves.

6. Soil erosion hazards

It is not at present possible to give a comprehensive and detailed review of the incidence and risks from soil erosion in Germany, owing to the lack of a sufficient number of detailed studies. Quantitative investigations of the erosional processes and data on soil losses exist only for a few areas. Among recent publications are those by Auerswald (1984, 1987), Bork (1983, 1988), Bork *et al.*(1985), Dikau (1986), Frielinghaus (1981), Jung and Brechtel (1980), Richter (1979, 1983), Rohdenburg (1987), Rohdenburg *et al.*(1986), Schröder (1985), Tille and Werner (1970), and Werner (1964).

Many researchers have recognised the fact that soils over extensive areas of Germany are threatened by soil erosion, and that the danger is increasing (Bargon, 1962; Bork, 1988; Richter, 1965; Sommer, 1983; de Vazquez *et al.*, 1985). The intensification of agricultural production, the spread of maize cultivation and the excessive enlargement of fields by the destruction of hedges and windbreaks, especially in the area of the former German Democratic Republic (GDR) have combined to produce not only an increase in visible signs of erosion and the number of local catastrophes, but also undoubtedly an increase in the slow insidious depletion of the soil layer, especially in areas of arable cultivation. Depending on the intensity of precipitation and on the types of land use, the potential erodibility of an area is principally determined by relief and soil properties. Figure 7.10 represents a first attempt to map the spatial distribution of areas susceptible to soil erosion by sheet wash in the former GDR. The parameters selected for this mapping (Flegel, 1958; Kugler, 1976) were slope angle (five categories), soil type (three categories based on texture) and land use (arable, forest and pasture). Data were obtained from existing relief, soil and land-use maps. Some clear regional

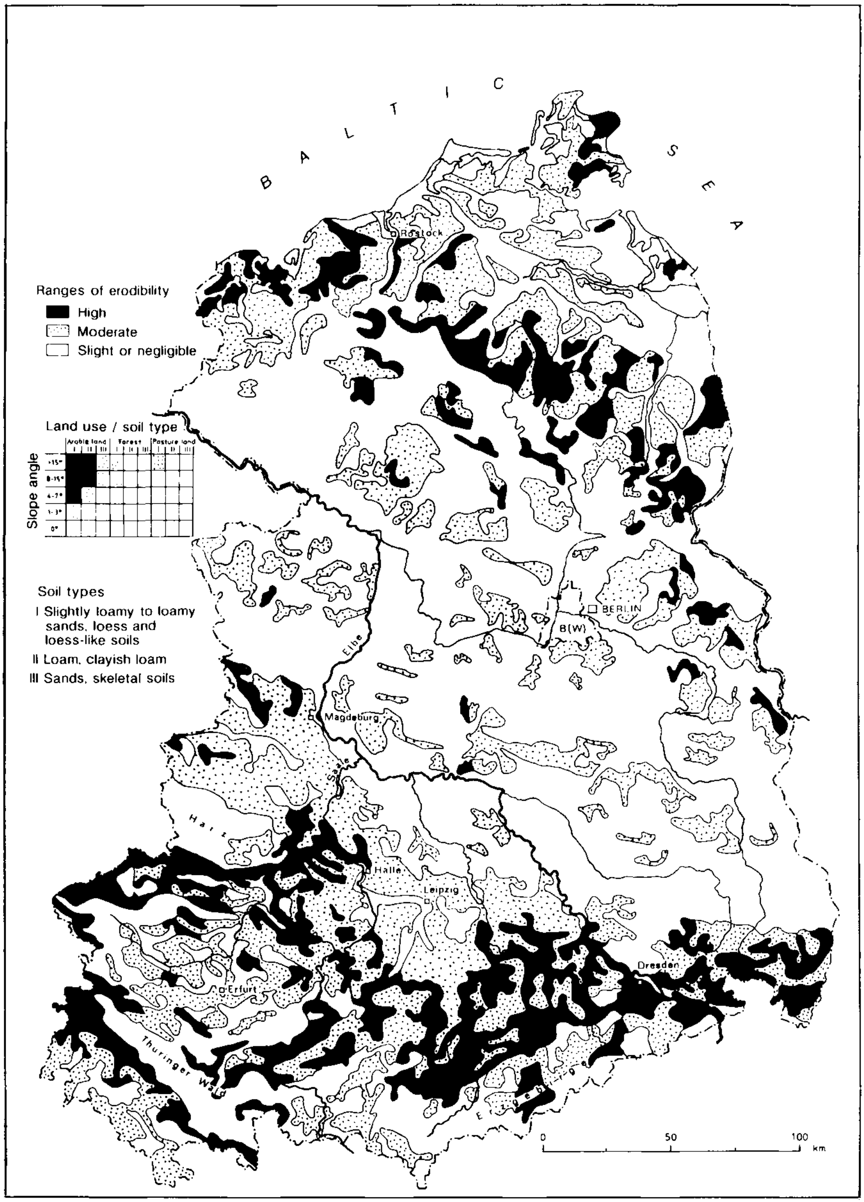

Fig.7.10. Soil erodibility by sheet wash, eastern Germany

patterns emerge. Areas with high or moderate erodibility occur, first, in the glacial moraine districts in the north, and secondly in the central and southern parts where hilly areas of loess are particularly threatened by sheet wash. Altogether, about 15 per cent of the former GDR is at relatively high risk from soil erosion, and another 35 per cent at moderate risk.

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GREAT BRITAIN

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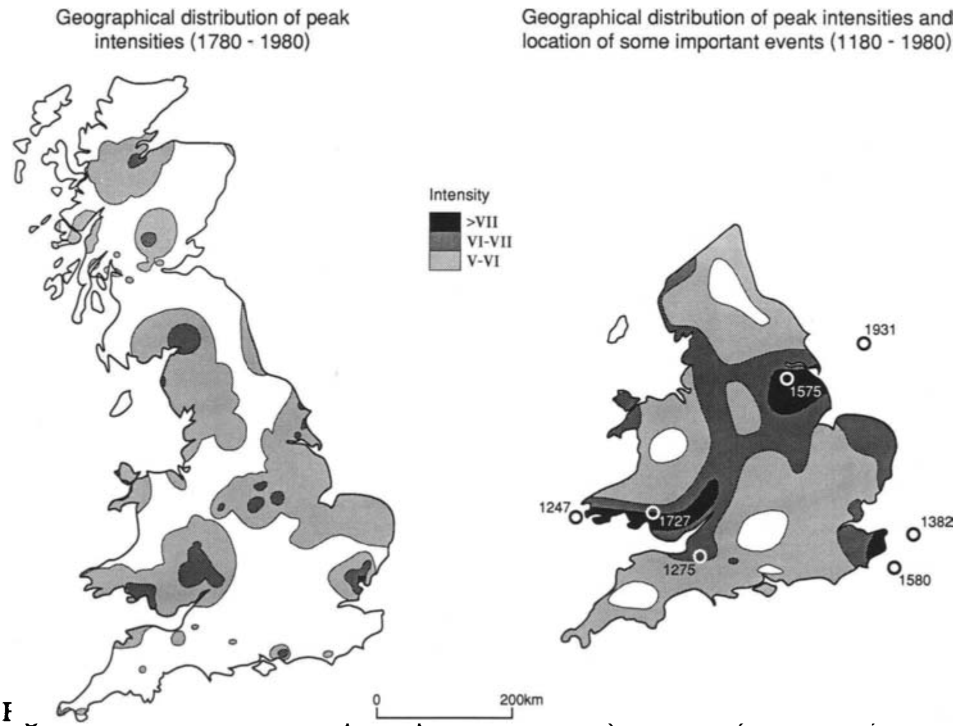
1. Introduction

In a global context, Britain must rank among the safest of countries in respect of natural hazards. Earthquakes are rare and of low magnitude, river flooding although occasionally serious is on the whole well controlled, landsliding is localised, coastal erosion is in only a few areas sufficiently rapid to cause problems, and heavy snowfalls and severe storms are infrequent or else they occur in remote or relatively unpopulated areas. On the other hand, there is a population of nearly 55 million with a marked concentration in lowland Britain: over the Midlands and the South-East, the average population density exceeds 200 per km^2. Further, one must take into account the existence of a highly developed infrastructure that is vulnerable to sudden disruption. It is not so much the potential for loss of life that is a cause for concern, as the costs imposed on the economy by the need for management of coastal defences, flood protection schemes, slope stabilisation and so on. However, serious loss of life has occurred in some past catastrophes: the death toll during the east coast floods of 1953 exceeded 300, and 144 people, mostly children, lost their lives in the landslip at Aberfan, south Wales, in 1966. This review will concentrate on earth surface processess and the occasional extreme events associated with them, though a few remarks on the seismic hazard will be made at the beginning.

2. Seismic hazards

Although the present-day seismicity of Britain is very low, earthquakes are by no means absent. They may be small and infrequent, but in terms of large modern engineering works (such as the Channel Tunnel, the Thames flood barrier, the Severn and Humber bridges, petrochemical installations and especially nuclear power plants), the possibility that damaging earthquakes may occur cannot be overlooked (Lilwall, 1976). Furthermore, for some purposes, such as the safe storage of nuclear waste, the longer-term seismic record is highly important.

Figure 8.1 (A & B) shows earthquake intensities for the last 200 and the last 700



F he location and dates of some important events: A.(*left*) for the period 1780-1980; B.(*right*) for the period 1180-1980 (after Ambraseys, 1985 and unpublished data; Ambraseys and Jackson, 1985).

years, compiled from data for more than 2000 events since 1185 by Ambraseys and Jackson (Ambraseys, unpublished report, 1985; Ambraseys and Jackson, 1985). The maps are strongly influenced by a few relatively high-intensity events; in the last 200 years, for example, the broad area of intensity > V (MSK scale) in eastern England largely reflects the important North Sea earthquakes of 1927 and 1931. For the 700-year period, the historical data are likely to be incomplete and far less reliable. However, as far as it is possible to judge, no earthquake in Britain in the last 700 years has been known to exceed magnitude 5.5 and maximum epicentral intensities have not exceeded VIII. At such relatively low activity levels, the ground surface is rarely broken by fractures: the main concern for the engineer is therefore not surface displacement but shaking or transient ground motion.

Figure 8.2 shows the distribution of known earthquake epicentres with M = 3 or more. Some groupings clearly pick out long-established geological trends. The Great

Glen fault, for example, striking south-west to north-east across northern Scotland is associated with numerous recent tremors of magnitude up to 4.5; and in south-east Wales and Herefordshire, over the last 150 years, about one-third of all British earthquakes with M > 4 have been located close to the Neath and Swansea Valley Disturbances. The damaging Hereford earthquake of 1896 belongs to this group. The incidence in off-shore areas is much less well-known and certainly underrepresented on the map, but some large events have taken place here, such as those of 1927 and 1931

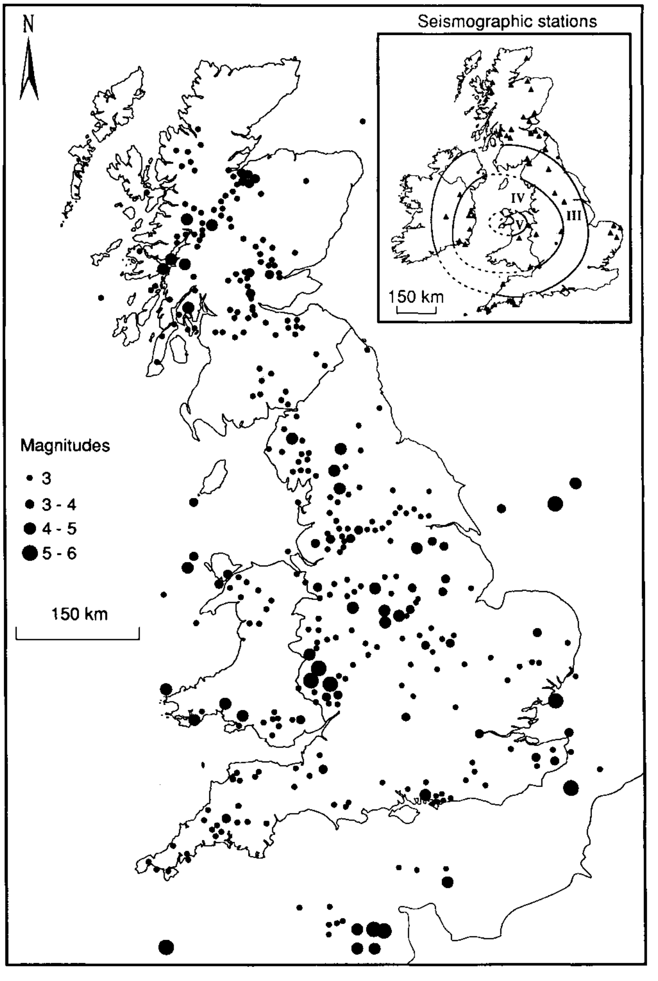


Fig.8.2 Distribution of earthquake epicentres with M = ≥3. Inset: Seismic recording stations operated by the British Geological Survey; isoseismal lines for the July 1984 earthquake (M = 5.4) in north-west Wales

east of the Humber, the 1382 earthquake near the north Kent coast and the major earthquake of 1580 in the Straits of Dover. Such events are of particular significance to such offshore engineering works as the Channel Tunnel and the North Sea oil and gas platforms. The frequent small tremors in central England are mostly related to coal mining and associated ground subsidence.

The largest intensity event so far recorded in Britain was that at Colchester, south-eastern England in 1884 (Meldola, 1886), felt over a radius of about 200km. More than 1000 buildings were damaged and three persons killed. Although the magnitude was only 4.4, its shallow focal depth (5km) was responsible for the relatively high level of damage, reflected in the probable epicentral intensity of more than VII.

Figure 8.2 (inset) shows the locations of seismic recording stations, operated by the British Geological Survey, and isoseismal lines for a recent "major" earthquake in July 1984, magnitude 5.4, centred in north-west Wales. Though minor in global terms, this was no negligible event, particularly because of the proximity of two nuclear power stations - Wylfa in Anglesey and Trawsfynydd to the south.

With 700 years of historical records and a century of instrumental records, it might be thought that predictions of the future incidence and scale of earthquake activity might be relatively secure. Unfortunately, the last 700 years have contained only small events, none greater than M = 5.5; extrapolation into the future and attempts to assess the probability of occurrence of larger events are fraught with danger since it is not known how statistically representative the last 700 years are. In view of the size and importance of many modern engineering undertakings, however, it is unwise to assume that Britain is immune from larger seismic events.

3. River flooding

Floods resulting from heavy rainfall and/or snowmelt represent a serious natural hazard to river valley populations in the UK. The history of flooding is well documented and there is a long tradition of flood management and control; nevertheless, the problem of flooding is a recurrent and widespread one and there is much scope for further mitigation of the hazard (Penning-Rowsell and Underwood, 1972; Newson, 1975; Ward, 1978).

The fundamental meteorological causes of river flooding in the UK are intense and/or prolonged rainfall and, to a lesser extent, snowmelt. The most intense rainfall occurs mainly in the western highlands, from western Scotland in the north, the Lake District in north-west England, western Wales, to the uplands of south-west England, but intense events also occur from time to time in the lowlands (Rodda, 1970). Indeed, the largest 24-hour rainfall ever recorded was near Dorchester, southern England, in July 1955, when nearly 300 mm fell. Bleasdale (1970) in a study of records since 1863 counted 151 falls exceeding 125mm in 24 hours; the areas affected can be quite small, often less than 100km^2. Meteorologically, short-period convective thunderstorms are the main cause, and therefore these intense events are most common in summer. The relief factor can also be very important in increased intensification. A well-documented example of flooding caused by localised intense rain was the severe flood of August 1952 at Lynmouth, Devon, when 229mm of rain fell in 24 hours on an already saturated upland catchment (Kidson, 1953). Other summer flood disasters include that in the Lud catchment of Lincolnshire in May 1920 when 23 people were killed, and the severe thunderstorm at Norwich in August 1912.

Extensive lowland flooding affects far larger populations and urban areas. This is mainly a winter phenomenon - three-quarters of all floods in Britain occur in the period October-March - and is linked to prolonged or repeated rainfalls usually caused by slow-moving depressions and moist south-westerly to westerly airstreams. Another important factor is the reduced evaporation of winter which encourages more extensive saturation of catchments; these then become very responsive to further heavy rain. The areas most at risk are the low-lying parts of the big river basins, notably the Thames, Severn, Trent and Yorkshire Ouse. For instance in February 1977, severe flooding affected the Trent lowlands following rainfall up to five times the normal for that month.

Another example was the flooding, from late September to December and including five serious flood events, which inundated large parts of the Exe valley, south Devon, in 1960 (Brierley, 1964). Exeter received 561mm of rain, two-thirds of its annual average, in 10 weeks. Rainfall intensities were not high: the maximum was 29mm an hour, which has a return period here of only 2.5 years. The Exe catchment, however, became totally saturated during the wettest October on record and further prolonged frontal rain generated rapid runoff.

Snowmelt in Britain presents a very variable risk, since many winters lack significant amounts of snow accumulation. To cause flooding, however, another factor is needed, namely rapid thawing of the snowpack. This can be due to a rapid rise in air temperature, but another very efficient melting agent is heavy rain, which of course adds its own dimension to the amount of runoff. Floods caused by rapid snowmelt are most common in Scotland, where they can account for up to a quarter of all flood events, and in eastern England, especially on the rivers draining the eastern Pennines. Snowmelt in March 1947, and again in March 1963, caused serious flooding extending from the Fenland to Yorkshire and Northumbria.

As well as meteorological causes, basin and channel characteristics also affect the incidence of river flooding. Possible factors include basin form (shape, slope, altitude, etc.), channel form (capacity, slope, roughness, etc.), geology and soils (storage capacity, permeability, transmissibility, etc.), vegetation and land use. For example, the intense rainfall at Dorchester in 1955 caused little flooding because of the permeable bedrock in the area, namely chalk. On the other hand, the severe flood of 1952 at Lynmouth reflected the relatively low permeability of this small catchment (only 101km^2), the saturation of the soil by antecedent rainfall, the steep gradient of the lower Lyn rivers, the convergence of the East and West Lyn just above the town, and the narrowness of the channel (Fig.8.3). In the case of the much larger river Severn, the extensive upper catchment (Howe, Slaymaker and Harding, 1967) comprises an area of high relief and generally impermeable rocks of north-central Wales, feeding into the lower part of the

Severn basin: at Shrewsbury, which has considerable flood problems (Harding and Parker, 1974), the river is still 130km from the sea but is flowing only 48m above mean sea level, a mean gradient to the sea of 0.038 per cent. Even lower gradients characterise the lower parts of rivers draining the Fens, the Somerset Levels and other flat areas close to sea level; special flood control measures operate in such areas where the main problem is how to store the river water in channels during the few hours around high tide, especially when the rivers draining into these plains are themselves in flood, and how to evacuate the water quickly enough as the tide falls.

Fig.8.3. The aftermath of the Lynmouth flood, August 1952. (Photo: *Press Association*)

Figure 8.4 shows the main river basins in Britain. In terms of area, the largest catchment drains to the Humber estuary (*c.* 25 000km^2), but since the latter is at sea level and not strictly a river, this basin is usually divided into separate components of which the largest two are the Trent and the Yorkshire Ouse systems. Other large basins in order of size are the Thames (if the Thames estuary is taken, the total area draining to it is about 15 000 km^2), the Severn/Avon (*c.* 11 500 km^2 drain to the Severn estuary), the Bedfordshire Ouse, the Tay and the Tweed in Scotland, and the Wye in south Wales.

In terms of mean annual flow, the Humber probably receives over 200m^{3}s, but this is not gauged. The largest true river in respect of discharge is the Tay with nearly 160 m^{3}s (see Table 8.1), though its peak flow attained 1990m^{3}s in January 1993. Another Scottish river, the Spey, also exceeded 1670m^{3}s in the flood of August 1970. However, it should be noted (Table 8.1) that the period of gauged record for most British rivers is quite short; and also that, except in the area around Perth, the Tay and the Spey flow through areas of low population. Nevertheless, the Perth-Tayside area experienced considerable flood damage to both housing and transport in the years 1990 and 1993, when the river rose to its highest known level since 1814.

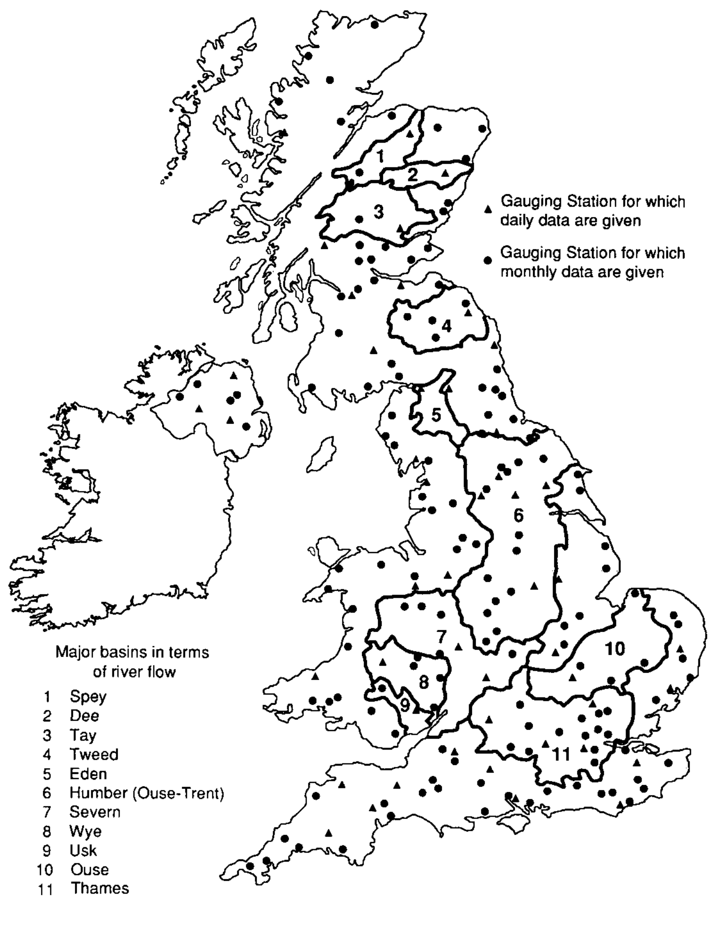


Fig.8.4. Major river basins in Britain in terms of discharge, and distribution of gauging stations (Institute of Hydrology, *Hydrological Data Yearbook*, 1988)

Table 8.1. Some basic data for the main British rivers (to 1988). *Source*: Hydrological Data UK, 1988 Yearbook, Institute of Hydrology, Natural Environment Research Council 1989, and subsequent Reports

River	Gauge	First year of record	Basin[1] area (km^2)	Max. altitude (m)	rain-[2] fall (mm)	Mean flow (m^3s)	Highest daily mean flow (m^3s)	Peak flow (m^3s)
Thames	Kingston	1883	9948	330	720	66.9	1059.0	–[3]
Trent	Colwick	1958	7486	636	777	85.9	854.9	957
Tay	Ballathie	1952	4587	1214	1422	158.8	1223.0[4]	1990[5]
Tweed	Norham	1962	4390	839	992	77.7	1138.0	1518
Severn	Bewdley	1921	4325	827	916	61.9	637.1	–[6]
Wye	Redbrook	1936	4010	752	1023	71.8	–	905
Spey	Boat o Brig	1952	2861	1309	1103	64.3	1089.0	1675
Eden	Sheepmount	1967	2287	950	1185	50.0	772.9	1357
Dee	Woodend	1929	1370	1310	1119	36.4	648.5	1133
Usk	Chain Bridge	1957	912	886	1389	27.8	585.4	945

Notes: 1. basin area above gauging point
2. computer-calculated rainfall over catchment area
3. not recorded before 1974; has not exceeded highest daily mean
4. highest mean flow for any river in Britain
5. highest recorded peak flow of any British river
6. not recorded before 1971; has not exceeded highest daily mean

Until 1989, the administration of matters connected with surface water discharge in Britain was effected through the regional Water Authorities. In 1989, their regulatory and river management functions were transferred to the new National Rivers Authority (NRA) in England and Wales (in Scotland, the River Purification Boards). The NRA has a general supervisory role and other statutory duties for flood defence. It operates more than 1200 river gauging stations. At more than half of these, river levels are routinely transmitted to the regional processing centres. From there, data are sent to the Institute of Hydrology at Wallingford, Berkshire, and collated for the Surface Water Archive. Summaries of data are published annually in Surface Water Yearbooks, beginning in 1935.

3.1. Flood estimation and prediction

One general problem in Britain is the relatively small size of the river basins, which means that there is little time for warning between the generation of excess water in upland parts of catchments, where few observers are available, and the arrival of the flood wave in the populated lowlands with their urban centres (Fig.8.5). Pressure for housing, especially in the south-east, has meant that many more properties are now at risk. The problem is particularly acute in the Thames NRA where the population is over 8 million. Despite the relatively dense cover of river and rainfall gauges, there is still a need for more automatic recording stations.

Fig.8.5. River flooding at Luddenden, Yorkshire in 1989. (Photo by kind permission of the *Halifax Evening Courier*)

Another general problem is the shortness of gauge records for most rivers which makes the estimation of peak discharge return periods problematic. To some extent, the gauge record can be extended by the use of historical data (documentary reports of floods, flood level marks, etc.), but in terms of the present-day flood hazard, more reliable short-term predictions are based on precipitation data (which are more plentiful than river flow data) and basin hydrological models.

The Flood Studies Report of the Natural Environment Research Council (1975) includes one of the most detailed studies in the world of the return periods of heavy rainfall, based on some 600 long-period rain gauges, averaging 60 years of record. A network of automatic rain gauges which routinely supply data to a central data bank are supplemented by direct rainfall measurements made by observers and, most importantly, by weather radar. In addition, the Meteorological Office has numerical predictive models that can provide heavy rainfall warnings of up to 36 hours.

Flood estimates are made from a set of basic variables for each river basin (slope, soil type, geology, land use, extent of urbanisation, etc.) which are put into hydrological models. Predicted flood levels arising from specific meteorological events, together with return periods, can then be derived. The NRAs, utilising these data and all other information can normally give at least 24-36 hours' warning of floods, depending on location.

3.2. Flood hazard mitigation

In such a densely populated country as Britain, land cannot be left unused; yet the risk of flooding cannot be ignored. With sufficient capital investment, flood risk could be wholly eliminated: the problem of flood hazard mitigation is not primarily a hydrological one but economic. The responses in Britain to the problem of flood risk fall into three categories, which are not mutually exclusive: all three can be and are employed in certain situations.

Protective engineering works with high capital cost, such as flood relief channels, embankments and flood storage basins (Nixon, 1963). Most river flood protection schemes in Britain involve the embanking of lowland rivers. There are no large flood control dams since the overall level of flood risk does not justify such expensive measures. Nearly all the upland reservoirs are designed primarily for water supply, not to assist flood control.

Forecasting and flood warning schemes, as already described.

Controls on land use, especially on the use of flood-risk areas for settlement and industry. Urbanisation itself can increase the local flood hazard because of the increase in the extent of impermeable surfaces, and the provision of efficient drains which deliver surface water to rivers at a high rate (Hollis, 1975). The merits of floodplain zoning are now well appreciated; but it requires strict planning controls and is essentially of long-term benefit, of no help to development and building that has already taken place.

An example of measures taken to ameliorate the flood hazard is that of the Bristol Avon. Its catchment is about 2200km^2, with a mean annual rainfall of 860mm, and it contains some important urban centres such as Bristol and Bath. The town of Bath has experienced more than 20 floods in the last 100 years, including serious flooding in 1960 and 1968. As a response, the channel capacity has been increased, with vertical banks in places, the channel has been partly realigned, and automatic sluices constructed to give temporary extra capacity for peak flows (Newson, 1975).

Several hydrologists have suggested that there is evidence for an increase in flood incidence in recent decades (e.g.Howe *et al.*,1967). There is a possibility that part of this increase may be due to a greater frequency of high-intensity storm events since 1940, as well as a possible increase in precipitation totals. February 1990 saw the highest river discharges for any month in at least 30 years, and flooding was widespread from

Cornwall to northern Scotland. In the Tay catchment, exceptional accumulations of snow in the winter 1992-93 followed by a rapid thaw led to the flooding on Tayside already mentioned. Here, the data suggest (*Institute of Hydrology Report 1992-1993*) that the return period of a 2000m^3/s flood has been reduced from >1000 years to about 100 years since 1989. As well as possible climatic change, however, another potent factor is the influence of man, especially through change in land use. Mention has already been made of the effects of urbanisation in accelerating runoff. Riverside development, including embankments and bridges, also reduces the effective channel capacity. In rural areas, agricultural drainage systems speed up the delivery of water to the rivers, and paradoxically, afforestation in its early stages can have the same effect. The initial stage of plough ditching prior to tree planting accelerates runoff, and it has been shown that this effect can last for up to 30 years until complete tree crown cover is achieved.

4. Mass movements

There are approximately 6850 recorded landslides in Britain, of which some 6000 are located inland and the remainder on the coast (GSL, 1986-87; Jones, Brook and Brunsden, 1987). The common landslide types include falls, rotational slides, translational slides, flows, creep and many complex varieties (Brunsden, 1985). Access to data on these is through the National Landslide Data Base which records basic information on age, soil and rock type, hydrology, relief, risk and cause (GSL, 1986-87; Jones and Lee, 1993).

4.1. Controls on landsliding

As described in section 2, Britain is a relatively stable area and landslides are rarely generated by seismic activity. Some active faults are occasionally associated with landsliding (Sissons and Cornish, 1982), but the main tectonic effects are indirect, through palaeo-structural conditions such as fault and joint weaknesses and available relief.

Sea level is a much more fundamental control because it is the base level for erosion, coastal attack and river incision. There have been major fluctuations of sea level in the recent past, and many relict landslides in the lower parts of river valleys are related to such changes. In the low sea-level glacial phases of the Quaternary, successive waves of erosion passed up the rivers to affect inland slopes. With the post-glacial rise in sea level, the sea reached the predecessors of the present cliffs about 5000 years ago, and there are now many drowned landslides offshore.

Climatic and vegetational changes in the Quaternary also had a profound effect. In northern and western Britain, large landslides are mostly associated with the deposition of vulnerable glacial and glacifluvial materials, the oversteepening of valley-side slopes by ice, slope unloading following ice retreat, and periglacial freeze-thaw conditions. In southern Britain, freeze-thaw, gelifluction, cambering and valley bulging, some permafrost and fluctuating water tables have locally left a maze of relict mass movement features, especially on the scarps of southern and south-eastern England (Skempton, 1976; Hutchinson, 1984). The effects of these processes were enhanced by changes of vegetation and forest clearance throughout prehistoric and historical time. The landscape has now largely recovered, but there are many landslide scars and shear surfaces that can be reactivated.

Geological factors in landsliding are fundamental because there is such a wide variety of vulnerable rock types, superficial materials and discontinuities. The scarplands and the south coast are classic areas of slope failure where permeable rocks frequently overlie impermeable strata. The east coast, broadly south of Flamborough Head, is composed of relatively non-resistant materials, suffering high rates of erosion (see section 5) while inland there are many lithologies susceptible to slope failure (Table 8.2).

Table 8.2. The relation between landslides in Great Britain and susceptible bedrock lithology. *Source*: GSL, 1986-87

Lithology	Number of landslides	Per cent of total
Clay	1871	21.8
Shale	931	10.8
Sandstone	818	9.5
Limestone	669	7.8
Interbedded argillaceous seds.	654	7.6
Interbedded arenaceous seds.	613	7.1
Siltstone and mudstone	466	5.4
Schist	455	5.3
Interbedded calcareous seds.	309	3.6
Grit	239	2.8
Igneous	167	1.9
Marl	90	1.0
Chalk	82	1.0
Other lithologies	177	2.1
Unknown	131	1.5
Total	8594	

Other factors affecting landsliding are locally important. Relief is a determinant even though most of Britain is not a high-energy environment. Slope failures are concentrated on the coast, and along some incised valleys or glaciated valleys inland. Aspect is not a significant factor. Human activity, however, including forest clearance, drainage, urbanisation, construction, vibration and mining, has often caused slope failure and should be considered a major cause of risk. Reactivation of dormant landslides is a serious problem.

All these factors have generated landslides not only at present but in the past, so that relict landslides are common. It is known that landslides are able to survive for long periods and that their shear surfaces persist long after the visible surface form has disappeared. They present a clear risk to any potential development. The time-scales involved range from the still recognisable scars of the 1952 Lynmouth disaster (section 3) to the 10 000-year-old slopes of the London Clay in Essex (Hutchinson and Gostelow, 1976). Landslides can often only be understood in terms of the slope history over a long period of time.

A final aspect that needs brief mention concerns the frequency and magnitude of landsliding. Climatic events are critical here, especially the intensities and durations of rainfall, together with antecedent and other weather conditions, and need to be carefully studied if landslide risk is to be properly evaluated.

All these factors control the geomorphological processes that cause landslides. The processes may be *preparatory* in that they make a slope susceptible to failure without necessarily initiating movement. Commonly they are *triggering* processes because they actually start the failure by altering the balance of the disturbing and resisting forces. When movement occurs, the processes may be *controlling* or sustaining in that they dictate the location, pattern, form, rate and duration of movement (Brunsden, 1985, 1987).

4.2. *The causes of landsliding*

Terzaghi (1950) distinguished between external causes that increase the stress, and internal causes that change the shear resistance of the slope-forming materials. Brunsden (1979, 1985, 1987) classified the causes into specific groups according to process (Tables 8.3 & 8.4):

Weathering determines regolith thickness, critical depth, soil properties and pore-water chemistry (Crozier, 1986; Carson and Petley, 1970; Moore, 1991; Moore and Brunsden, 1993).

Erosion alters slope geometry, plan and profile form, regolith thickness, loading, unloading and short-term pressures (Skempton and Hutchinson, 1969).

Subsidence may be caused by karst processes, salt or gypsum removal, seepage or mining, and may result in spectacular failures (Ward, 1948; Hutchinson *et al.*, 1981).

Deposition of sediment includes loading by fill, waste or rapid natural loading (e.g. by earth falls). When undrained conditions occur there is serious risk (Hutchinson, 1970; Hutchinson and Bhandari, 1971).

Shocks and vibrations are usually connected in Britain with construction, traffic or explosions rather than seismic causes. They cause sudden increases in horizontal stresses, reduction in strength, disturbance of bonds and cements, and change in ground-water level or pressure.

Change of water regime is the most important single cause of failure. It involves the unit weight of the soil, change in groundwater level and pressure, change to shear resistance, elimination of surface tensions, removal of bonds and cements, and changes in weathering, wetting and drying. The effects occur at all scales and locations. The subject also involves consideration of precipitation, antecedent conditions, isohyetal pattern, coincidences in controls and critical soil parameter thresholds.

Table 8.3. Geomorphological processes and other phenomena that contribute to landsliding in Britain. *Source*: GSL, 1986-87

Group	Total	Per cent of total	Inland	Per cent of inland	Coastal	Per cent of coastal
Weathering	589	14.6	534	16.0	55	7.9
Erosion	1688	41.8	1205	36.1	483	69.6
Subsidence	97	2.4	58	1.7	39	5.6
Deposition	119	2.9	100	3.0	19	2.7
Shocks and vibrations	89	2.2	84	2.5	5	0.7
Change in water regime	1452	36.0	1359	40.7	93	13.4
Totals	4034		3340		694	

Note: Within these groups, the following processes or phenomena have particularly marked effects: freeze-thaw, basal erosion, excavation, erosion by seepage, deposition by natural or human agencies, fault movement, intense or prolonged precipitation, change in vegetation.

4.3. The landslide hazard

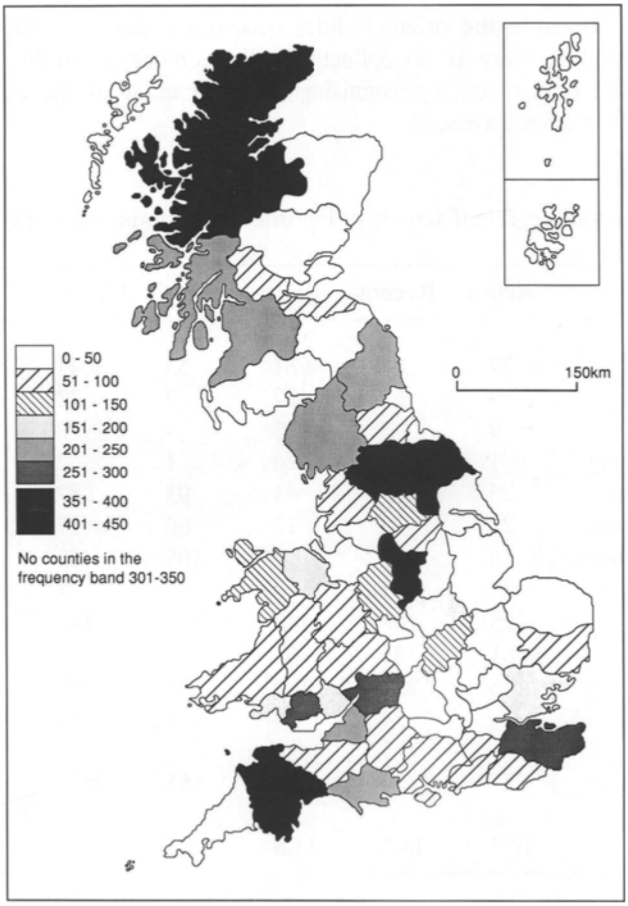
These considerations mean that the landslide hazard in Britain is not simply a matter of failure being linked to especially hazardous places such as volcanoes, steep slopes or rapidly eroding catchments. In Britain, new active landslides tend to occur in obvious locations such as eroding sea cliffs or incised valleys. Debris flows may occur in intense storms in highland areas, as do rock bursts and rock falls. The greatest dangers appear to be from coastal rock falls or ill-advised construction works. The numbers of deaths are small, averaging perhaps two or three people a year, but these figures are distorted by just two large events in recent times. The cost is certainly several million pounds a year, but this is no more than an estimate.

The main problem in Britain is that, because landslides are largely caused by changes in water regime, climate, vegetation and sea level, many of our landslides are relict (Table 8.4). The danger lies in their reactivation and in the widespread nature of the failure surfaces. Because the original slides occurred under very different conditions from those of today, there is no collective folk memory of an instability problem. Investigations are only recently recognising this, and many of the examples listed in Table 8.5 could have been avoided.

Table 8.4. Types and degree of activity of landslides in Britain. *Source*: GSL, 1986-87

Type	Active	Recent	Relict	Fossil	Unknown	Total	%
Unclassified	77	288	281	53	3041	3740	54.6
Falls	79	67	7	7	22	182	2.7
Topples	9	3	15	-	8	35	0.5
Spreading/sagging	1	-	26	1	2	30	0.4
Single rotational	25	235	44	93	82	479	7.0
Multiple rotational	20	29	17	60	57	183	2.7
Successive rotational	16	7	9	105	15	152	2.2
Non-rotational	22	35	6	38	17	118	1.7
Planar	225	208	142	18	148	741	10.8
Flows	81	143	61	8	61	354	5.2
Complex	176	222	189	58	57	702	10.2
Other	-	-	9	114	11	134	2.0
Totals	731	1237	806	555	3521	6850	100
%	10.7	18.1	11.8	3.1	51.4	100	

Although relict slides are broadly distributed, there are also heavy concentrations in some geologically favourable locations (such as below the escarpments of south-central England, in the South Wales valleys, or in the Highlands) which pose serious economic problems for these areas. The cost to individuals, local communities, national services and industry is not known but must be much higher than most would anticipate. For example, the cost of transport delays is unknown. Landsliding is a significant hazard in areas of coastal erosion; wherever major new road schemes are contemplated (e.g. the Bridport-Charmouth by-pass in Dorset); at new dam sites; and for certain towns (e.g. Ventnor in the Isle of Wight) that are actually built on landslide complexes. Fortunately, the Department of the Environment is stimulating new research in order to reduce these risks. Although the hazard is widespread and serious, we are beginning to understand its scale and nature. The fact that reactivation and renewed movement, rather than



initiation of totally new slides, is the main risk means that the level of hazard should be reduceable.

4.4. Landslide impacts

The risk from landsliding as defined by the United Nations (Varnes, 1984) - degree of loss, injuries, damage and loss of economic activity - cannot be estimated for Britain. The National Landslide Data Base records the events that have had an actual impact on the community, their location (Fig.8.6) and the known degree of damage, but the data are incomplete. Table 8.5 gives a broad set of examples.

Eighty-nine per cent of the known landslides (totalling 6850: see Table 8.4) have had no direct impact on human activity. Of those that had an impact, 22.5 per cent were

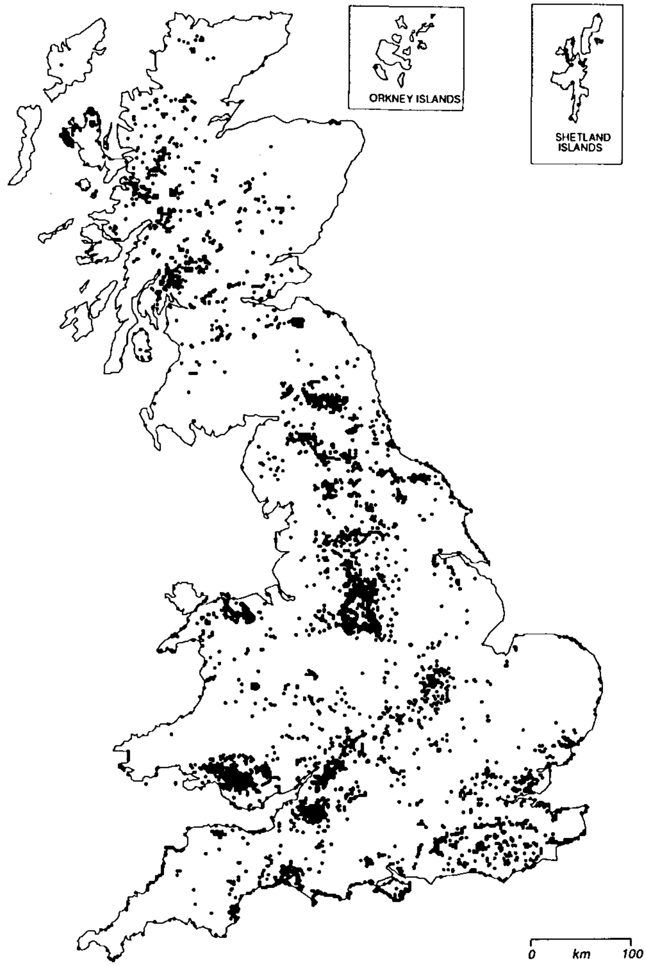


Fig.8.6 (a) (*facing page*) Numbers of recorded landslides in Britain according to county; (b) (*this page*) The distribution of recorded *active* landslides in Britain. *Source*: The Department of the Environment, Review of research into landsliding in Great Britain by Geomorphological Services Ltd.

located in the south-east, 7.9 per cent in the south-west, 7.2 per cent in the Midlands, 21.3 per cent in Wales, 4.5 per cent in northern England, and 3.5 per cent in Scotland. In more detail, the main problem areas are the Weald, the London Basin, the Cotswold Hills, the southern Pennines, South Wales, the Welsh Border and the east Midlands plateau. Geologically, they are concentrated on the escarpments in areas of London Clay (Tertiary), Cretaceous, Jurassic and Triassic rocks, and on the Carboniferous shales, sandstones and mudstones of the Severn valley, the South Wales coalfield and the southern Pennines. The main coastal areas of serious landslide impact are to be found in Gwynedd, Lyme Bay and Purbeck (Dorset), the Isle of Wight, the Chalk cliffs of north Kent and Sandwich, Hythe, and in east Anglia, the Cromer-Overstrand coast. In Scotland, the area of the Storr on Skye is one of Europe's major landslide complexes (Tertiary basalt over Mesozoic clays).

The reported density of landslide impacts is low and rarely exceeds one per 100km^2 (Greater London 1.2, Surrey 1.25, Avon 3.86, Gwent 4.65, Mid-Glamorgan 9.03, West Glamorgan 4.65). These figures are misleading; many impacts on isolated roads or structures in mountain areas go unreported in the scientific literature. Conversely, the concentrations of impacts in lowland areas reflect the population distribution and density of use of the infrastructure, but even this relationship is not clear. For example, Greater London has a moderate density of impacts with a population density of the order of 10 000 per km^2. Avon, Gwent, Mid- and West Glamorgan are examples of counties with population densities between 100 and 1000 per km^2, but have a high

Table 8.5. Examples of the landslide hazard in Britain

Date	Location	Type of failure	Comment
Accidents: (all coastal)			
1925	Bascombe	Rockfall	3 dead, 5 injured
1959	Alum Bay	Sand run	1 dead, 3 injured
1971	Kimmeridge	Rockfall	1 dead
1975	Swanage	Rockfall	1 injured
1976	Swanage	Rockfall	1 dead
1977	Lulworth	Rockslide	3 dead, 1 injured
1979	Durdle Door	Rockfall	1 dead
1986	Newquay	Mud and rockfall	1 dead
Preventive measures:			
1970s	Thanet		Removal of rock stacks
1970s	Dorset		Estimated hazard cost £2.5 million per year
1965-78	West Bay		Remedial works cost £2.8 million
1978	West Bay		Cliff regrading cost £1 million
1981	Malvern	Mudslide	Reservoir abandoned
1982	South Wales	Complex	182 families moved
1986	Seaford	Chalk fall	Public warnings
1986	Ystalyfera[a]		30 families moved

(Table 8.5 continued)

Damage to infrastructure:

1682	Runswick[b]	Mudslide	Whole village lost
1829	Kettleness[b]	Mudslide	Village slid into sea
1890-1990	"	"	Regular movement
1961	"	"	Access destroyed
1977	"	"	Rose cottage slide blocked services

Coastal landslide complexes

1940s to present	Fairlight	Mudslide and rock falls	3.5m lost per year. Cost £12 million in 4 years. In next 100 years, 46 houses under threat.
1930	Luccombe	Mudslide	Property damage
1890 to present	Ventnor, I.O.W.	Rotational slides, block glides, some deep-seated	Movement up to 1cm per year; 6000 people affected, 50 houses demolished.

Road damage

1802-1977	Mam Tor, Derbyshire	Complex, deep-seated	Major Pennine road affected
1953	Scottish highlands	Debris slides	Road repairs cost £2.5 million
1961-62	Waltons Wood	Deep-seated	£600 000 repairs (M6 motorway)
1964-66	Sevenoaks by-pass	Rotational and mudslides	Road re-located
1968	Fernhurst and Ide Hill[d]	Complex mudslide	Road and house damaged
1969	Swindon	Rotational slide	Roadworks disrupted (M4)
1960-90	Charmouth	Complex	Road damage (A 35)
1970s	Taren, Taff valley[a]	Complex, deep-seated	Road repairs cost £3 million
1971	Chudleigh	Planar slide	A 38, construction problems
1971	Broadway Hill	Rotational slide	A 44, regular movements
1970s	Patree-Staffin (Skye)	Complex, deep-seated	A 855: Storr landslide slow moving
1970s	Swainswick, Bath	Complex	A 46 moving
1974	Portway, Avon	Rockfall	Road unsafe
1983	Bethesda, Snowdonia	Debris slide	A 5 road blocked, cost £146 000
1990	Fraddon Down	Flowslide	Blocked road and drainage

(Table 8.5 continued)

Railway damage (three examples only given)			
1915	Folkestone Warren	Complex rotational	Line displaced 50m; train derailed
1965	Glen Ogle	Slide	Railway closed
1969	Stoneferry	Slide	Line blocked for 5 months
Damage to dams			
1864	Dale Dyke	Rotational slide	Village destroyed, 250 dead
1984	Carsington	Rotational slide	Large earthfill dam failed, cost £3.25 million in claims so far
Damage to housing and settlements			
1860-75	Hedgemead, Bath	Complex	135 houses destroyed; damage to sewers and pipes
1882 to present	Irwell, Salford	Rotational slide	Recurrent house and road damage
1909	Pentre[a]	Flowslide	1 death, 5 houses damaged
1916	Pentre	Spoil loading	Houses and hall demolished
1954-80	East Pentwyn[a]	Complex rotational	12 houses demolished, 28 at risk; Drainage cost £1 million
1961	Pont-y-Gwaith[a]	Slide	Clay slide into house
1966	Aberfan[a]	Colliery spoil flowslide	Whole community destroyed; 144 killed
1970s	Bwlch-y-Gwynt[a]	Threat from 50m overhang	£41 million to remedy
1986	Exwich Farm[c]	Slide	Major slide reactivated

Footnote: In a Table such as this, it is clearly impossible to list every event; enough examples are given, however, to illustrate the level of hazard presented by landslides in Britain, and the growing body of knowledge about them. Certain areas have been more intensively studied than others. For example, in the Rhondda valleys of South Wales, a Department of the Environment Survey found no less than 585 slides; a more local survey by Halcrow found 346 slides in 9 per cent of a parish area. It is estimated that 26 slides will involve repair costs between £100 000 and £3.5 million, and 24 will cost from £5000 to £100 000.

[a] South Wales; [b] Yorkshire; [c] Exmouth (Devon); [d] Sussex

density of impact. On the other hand, there are also counties with medium population densities (such as Berkshire, Essex, Isle of Wight, Kent, Leicestershire, Nottinghamshire, South Yorkshire, Surrey and West Sussex) and a moderate landslide impact.

Most recorded impacts affect road, rail and other community property (79.3 per cent). General service infrastructures, piping and cabling are also very vulnerable. In towns such as Ventnor (Isle of Wight) and Lyme Regis (Dorset; Fig.8.7), sewage and water

Fig.8.7. The Cliff House landslide at Lyme Regis, 1962. Vegetated and degraded cliffs in Liassic clay can be traced across the photo, which over time have been developed for housing, especially where the Cobb Road descends the cliff. During the slide, Cliff House was destroyed, but the shear surface did not displace the esplanade.

services are affected as well as damage to houses. Man is himself the culprit in many cases: for example, 88 per cent of rail and 66 per cent of road impacts result from changes of slope angle involved in the construction works.

In section 4.3, the real but often hidden problem of relict landslides was emphasised. The risk data (GSL, 1986-87, series D, vol.II) show that nearly 19 per cent of landslide impacts result from the disturbance of ancient slides. Of course it is expected that active (22 per cent) and recent (56 per cent) landslides would often be associated with risk, but it needs to be stressed that, in Britain, a principal problem is the potential damage to engineering or other projects resulting from the disturbance of relict shear surfaces or deposits. A classic example is the damage to the Sevenoaks by-pass (Kent) when a Late-glacial slide dated to 10300-10800 BP (pollen zone III) was inadvertently reactivated during construction. Similar examples have occurred at Waltons Wood on the M6 motorway and the Daventry by-pass in the Midlands (1979). Elsewhere, the presence of recognised relict or active slides has led to major expenditure on investigation or remedial measures.

A final point to note is that the areas of landslides that cause damage are usually small: Britain is not, geomorphologically, a high-energy environment. Sixty-three per cent of the landslides included in the National Landslide Data Base are smaller than $0.25 km^2$, while 5 per cent are between 0.25 and $0.5 km^2$. Britain tends to be affected by small rock falls, debris slides and complex movements. Massive rock falls, avalanches or surges are rare. Loss of life in each event is low and events such as Aberfan, south Wales, in 1966, when 144 persons were killed, are fortunately extremely rare (Miller, 1974).

A note of caution is necessary when studying the data. These only record the landslides that are reported in the scientific literature and major reports. Many areas have not yet been investigated in the field. The risk is undoubtedly greater than the Data Base would suggest, and this summary should not be considered as a final assessment.

Acknowledgements: Mr Mark Lee and Dr Roger Moore have been very helpful in providing the information from the National Landslide Data Base. Some of the other data are from original reports of the "Review of Research into Landsliding in Great Britain" prepared by GSL under Department of the Environment Research Contract PECD 7/1/161.

5. Coastal hazards

There are two main types of hazard that affect British coasts: coastal flooding and cliff erosion. The first of these presents a risk on all low-lying coasts but especially in south-eastern England much of which is experiencing relative subsidence at the present day. Cliff erosion together with coastal landslipping is most serious in those areas of soft or unstable rocks with considerable exposure to storm wave attack. Artificial measures undertaken to protect cliffs or prevent flooding are amongst the most costly of all hazard-prevention schemes, but are essential because of the extent of coastal settlement and development and the presence of large centres of population. The greatest single disaster was the east coast flooding of 1953 when 80 000 ha were inundated and over 300 people lost their lives.

5.1. Cliff erosion

Rates of cliff recession in parts of eastern England are the fastest in Europe, in many places exceeding an average of 1m a year. The loss of land is in places highlighted by destruction of cliff-top houses, the threat to local roads, and even by the total disappearance of some small villages in historic time. Less noticeable but significant is the loss of agricultural land. Nevertheless, the extent of the problem should not be exaggerated, as the Royal Commission on Coast Erosion (1911) noted. Using data from comparison of Ordnance Survey maps for a period of about 35 years, the Commission found that about 2690 ha were lost to the sea, against a gain of about 19 400 ha from accretion and reclamation. On the other hand, much of the gain was from silting in river estuaries where the components of river and marine deposition cannot be separated. It is also necessary to record that loss of land by erosion would be much more serious were it not for the existence of sea defence works: the other side of the coin is that sea defence works themselves can frequently cause increased erosion on another neighbouring section of coast through their interference with natural beach processes.

A whole set of geomorphological processes is subsumed under the heading of cliff erosion. Wave attack undermining the cliff base is of course an essential component, without which cliffs become degraded through time and cease to retreat, but in terms of volume of rock moved, it represents a minor contributor (perhaps only 10-20 per cent) compared with other processes at work on the cliff above. These include, first and foremost, mass movements such as rotational slips, rock falls, mud and sand flows, and secondly other sub-aerial processes such as slope wash, creep, weathering (freeze-thaw, solution, etc.) and wind removal of fines. Much of this activity, but especially the element of mass movement, is spasmodic in time, occurring in 10-year to 100-year cycles of cliff retreat. Short-term measurements of cliff erosion can therefore be very misleading (Cambers, 1976).

The fastest rates of erosion and cliff recession are associated with the soft Quaternary formations of parts of Eastern England, notably Holderness (at one locality, averaging 1.75m per year over 37 years: Valentin, 1971) and East Anglia. At Pakefield, the average over 64 years is 2.94m per year; at Easton Bavents (near Southwold), 3.48m per year over 21 years; while at Ness Point, 5.36m per years over 22 years bears witness to the shortage of protective beach material caused by Lowestoft harbour impeding the longshore drift. In south Dorset, Jurassic and Lower Cretaceous clays and sands form unstable cliffs rising to 190m at Golden Cap. Rates of recession on the south Dorset coast have averaged 0.6 to 1.0m per year over the last 5000 years (Brunsden and Jones, 1976; Bray, 1990). Another factor, apart from rock type is important here, namely exposure and high wave energy: the coast is open to the Atlantic in a south-westerly direction, and in severe storms, waves are seen to overtop even the 20- metre-high shingle barrier of Chesil Beach. The coast of south-east England is generally less vulnerable because of the proximity of the French coast (for rates of retreat, see May, 1967, 1971, and Table 8.6), but from Lowestoft northwards, the bulge of East Anglia and the Lincolnshire coast possess a sea fetch of 600km or more in a north-easterly or northerly direction from which occasional storms arrive.

Table 8.6. Some maximum rates of coastal retreat

Locality	Lithology	Erosion rate (m per year)	Period (years)	Source
Holderness	Glacial deposits	1.75	100	Valentin (1954)
Holderness	Glacial deposits	10.00	9	Pringle (1985)
Norfolk	Glacial deposits	1.80	100	Clayton (1989)
Suffolk	Glacial deposits	5.10	25	Steers (1951)
Suffolk	Glacial deposits	1.60	164	Robinson (1980)
Kent	London Clay	2.20	99	Hutchinson (1973)
Kent	London Clay	2.00	33	So (1967)
Sussex	Chalk	0.91	41	May (1971)
Dorset	Chalk	0.46	80	May & Heeps(1985)
West Wales	Greywacke/mudstone	0.06	90	Jones & Williams (1991)

Defence against cliff erosion is not only expensive but usually unsightly (and in the case of high cliffs is largely impracticable in any case). Coastal towns can be involved in huge on-going costs, which have to be set against the value of or the income from the amenity which they are trying to protect. For the central part of a town, with its traditional promenade, modern concrete sea walls can be normally effective; but their weakness always lies in their terminations, where wave attack can rip out the rock or other material behind (Fig.8.8). Cliff retreat here then leaves the wall dangerously vulnerable. Outside urban areas, the cost of engineering works to combat cliff retreat should be carefully set against the value of the land or structure to be protected. Local people may be naturally opposed to such a viewpoint, but in reality, re-housing elsewhere may be a much less expensive solution than trying permanently to defy natural coastal evolution. The recent (June 1993) collapse of the Holbeck Hall Hotel, Scarborough, highlighted the dilemma.

Another important facet of the coastal protection problem is the visual impact of the defence works: bare concrete walls can destroy the scenic value of the coast they are designed to protect. A good example of this dilemma is the case of Chesil Beach in southern England (Heijne *et al.*, 1991). In the winter of 1978-79, severe storms caused

Fig.8.8. The western end of the sea wall at West Bay, Dorset, built to protect the cliffs (Jurassic) from wave attack. Large boulders (not visible) have been placed beyond the end of the wall, but the sea is already beginning to attack the exposed end and the sediments behind. The cliffs beyond are unprotected and may be expected to retreat, thus further increasing the vulnerability of the wall. (Photo: C.Embleton)

waves to overtop this huge shingle barrier, flooding the town behind. To combat future recurrences, flood drains were installed on the landward side; metal gabions were then placed on part of the top of the barrier with the aim of strengthening and raising this unique shingle structure. From an engineering point of view, the measures have been largely successful; on the other hand, the gabions stand out as a crude eyesore on what should be an unspoilt coast. A further problem is uncertainty over the longer-term geomorphological response to such interference, especially in view of the fact that the beach is no longer receiving significant amounts of shingle from the west because of other human interference here.

For the past few decades it has become increasingly realised that one of the best forms of protection against coastal erosion is a substantial natural beach and/or dune system. It preserves, even adds to, the scenic amenity and is a valuable tourist asset in itself; in equilibrium with the coastal process system it maintains itself; and against exceptional storm conditions can be remarkably resilient, as has been repeatedly shown around British coasts (e.g. in parts of eastern England during the 1953 flood disaster: Steers, 1953). For these reasons, natural beaches should be jealously guarded, and removal of beach material for commercial purposes strictly forbidden. In the past, and still to some extent at present, some coastal resorts attempted to increase the volume of material on their beach by erecting groynes to hinder longshore drift. Such devices, however, invariably have an adverse effect on the next stretch of beach along the coast which will be starved of beach material and suffer erosion. This raises the important and general issue that coastal management should be conducted in the framework of a long-term regional strategy; but until recently (see below) there has been no legislative mechanism in Britain to allow this.

5.2. Coastal flooding

On low-lying coasts, but especially those where land reclamation and settlement have been carried out on areas below high-water mark, inundation by the sea at times of exceptional high tides or onshore storms is a continual threat. Most parts of the British coast have a tidal range greater than 2m; at Skegness in eastern England it reaches 6m, while the Bristol Channel has an exceptionally high tidal range of more than 12m. Storm surges can raise local water levels further by as much as 2 or 3m. Part of this can be due to the inverse barometric effect on sea level of the passage of a deep depression (up to a metre or so in the British area); the other component is the sea surface slope induced by strong persistent winds, particularly in relatively constricted seas (Fig.8.9). In the absence of better probability data, the coincidence of a storm surge with high tide can only be considered a matter of chance - even more so coincidence with a high spring tide - but the effects of such a coincidence of timing can be potentially disastrous. In January 1953, a powerful storm surge in the North Sea, driving water into the relative bottleneck of the English Channel and up the Thames estuary, raising sea levels by more than 3 m above normal high tide, fortunately did not quite coincide with the time of peak tide. Nevertheless, 800km^2 of land were flooded by the sea in eastern England (Fig.8.10) and the death toll exceeded 300.

The magnitude of the 1953 flood disaster prompted serious consideration of the need to provide London with flood protection. In 1953, considerable areas to the east of the city were inundated, and enormous damage and considerable loss of life resulted. Here at least regional planning was possible, since the whole area at risk fell within the London County Council (later the Greater London Council) administrative area; furthermore, plans were drawn up on a long-term basis to take account of coastal subsidence (see below). Work on the Thames Barrier was completed in 1982 at a cost of (then) £450 million; additional expenditure of about £300 million was needed to raise and strengthen the banks of the estuary downstream. The Barrier (Fig.8.11) consists of ten movable steel gates which, when open, lie horizontally on the bed of the river; in 15 minutes they can be fully closed in the vertical position. The maximum level of protection (the top of the gates) is 7.2m above mean sea level (cf. the maximum level attained by the tide in the 1953 flood was 5.3m). The 7.2m maximum defence level will provide protection against the 1000-year event until about the year 2030. Beyond this, the level of protection will gradually decline as global sea levels rise and slow land subsidence in south-east England continues. It is probable that, after 2100, a new Barrier will be needed, possibly across the lower estuary, similar to the Delta Scheme in Holland.

Fig.8.9. Distribution of storm surge elevation (m) at 12.00 GMT on the 26th of February 1990, the time of high tide and maximum water level.

A major element in the flood defences of the Thames estuary is the system of embankments whose top level was raised to just above the maximum height of the gates when closed. Embankments likewise protect other low-lying coastal areas around Britain, but most date back many decades or to the last century; many consist of earth and are in urgent need of renewal, armouring and strengthening. Responsibility for the maintenance of such flood defences is divided among a plethora of owners and administrations. The consequences of embankments being breached during severe storms can be disastrous.

In the winter of 1989-90, the coastal embankment at Towyn in north Wales was broken, allowing the sea to flood in over a residential area; 14 people died. The

Fig.8.10. Flooding of Canvey Island in the Thames estuary on the 2nd of February 1953, two days after the disastrous East Coast Floods. The breached sea wall in the foreground is being repaired. The whole population of the island, about 12 000, was evacuated; the death toll here alone was over 100. (Photo: *Press Association*)

responsibility for maintenance of the embankment in this case lies with British Rail, for the embankment was built primarily to carry the railway across a low-lying alluvial area, not for coastal defence.

Relative sea-level trends are a central factor in the long-term protection of coastal areas (Tooley and Jelgersma, 1992). Several processes are involved: contemporary global sea-level rise (some estimates put this as high as 6cm per decade), tectonic subsidence of the North Sea basin and other areas, and a complex element introduced by post-glacial isostatic recovery whereby in general Scotland is rising (in parts faster than present sea-level rise), and in the extreme south-east of England a forebulge linked to earlier glacio-isostatic depression of northern Britain may exist. The net effect ranges from relative emergence of more than 5mm a year in some places to as much as 7 or 8mm a year of relative submergence in others. Unfortunately, tide-gauge data are either unreliable or unclear in their significance, due to the shortness of many records, changes

Fig.8.11. The Thames Flood Barrier, Woolwich. One of the gates (to the right of centre) is partially closed. (Photo: C.Embleton)

in gauge location or instrumentation, and changes in the gauge environment (e.g. resulting from harbour alterations). In the Thames area, relative sea-level rise is probably 1-2mm per year (Valentin, 1953; Rossiter, 1972; Aubrey, 1985).

5.3. Coastal management

In a word, this can hardly be said to exist so far in Britain, on anything more than the local scale. The problem is that it is the responsibility of far too many separate and uncoordinated agencies, from national level to local, and from Government to private. The result has been that the response to a potential hazard is often to ignore it until disaster happens.

Coastal legislation in Britain has grown up piecemeal within frameworks of existing administrative convenience, so that many agencies, authorities or private individuals have had an overlapping (sometimes conflicting) interest in a particular piece of coast, but that there has been no overall body resolving disputes or problems, or capable of carrying out forward planning. The following is a brief synopsis of a tangled situation.

The Crown owns all the foreshore and intertidal areas in the UK, through the Crown Estate Commissioners; but places no bar (fortunately!) on public access. At Government level, there are Acts of Parliament: after the Royal Commission on Coast Erosion of

1911 (already referred to), Parliament introduced measures for coastal protection in 1913; further legislative changes in 1949 were embodied in the Coastal Protection Act whose implementation is undertaken by district or metropolitan councils. The latter can apply for government grants (up to 80 per cent of costs) for defence works against coastal erosion. On the other hand, sea defence against flooding is the prerogative of the Ministry of Agriculture, Fisheries and Food which legislates for all drainage and flooding problems, river or coastal (e.g. the Land Drainage Act, 1976, in England and Wales, the Flood Prevention Act, 1961, in Scotland). These Acts are administered by the National Rivers Authority (NRA) in England and Wales or the Scottish drainage boards. The NRA currently spends about £250 million a year on flood defence, but it has no powers of control over what sort of coastal development the local planning authorities may permit. Planning controls on coastal development are often very lax, as local authorities are usually anxious to encourage more settlement, assuming that coastal flood defence costs will be borne by central government. For example, since the Towyn flood of 1989-90 in north Wales already mentioned, a new sea wall has been built; and now even more development, especially of retirement bungalows, is taking place in an area lying up to 1m below the level of the 1989-90 flood.

Some sections of coastline fall within the National Parks of England and Wales, and are managed by the Government-sponsored Countryside Commission. Yet other, smaller sections are watched over by the Nature Conservancy as, for example, designated Sites of Special Scientific Interest. Finally, some voluntary organisations play an important role, especially the National Trust which manages (through leases, covenants or outright ownership) more than 600km of British coastline and is often considered to represent the best coastal management in Britain.

The Government has recently begun to tackle some of these legislative and planning problems, e.g. in the 1992 report of the Parliamentary Select Committee into coastal planning. The 1949 Coastal Protection Act did in fact contain procedures for resolving regional planning conflicts, but these have not generally been invoked, probably because of lack of understanding of the coastal geomorphology rather than an unwillingness to plan. Since the late 1980s, some important advances have been made regarding regional coordination of coastal defences, mainly as a result of the work of a number of informal coastal planning groups (e.g. the Carmarthen Bay Coastal Engineering Study Group, the Holderness Coast Protection Project, and the Standing Conference on Problems Associated with the Coastline (SCOPAC)). These initiatives have been followed by the establishment of more formal bodies such as the Welsh Coastal Groups Forum (under the Welsh Office) and the Coastal Defence Forum (Ministry of Agriculture Fisheries and Food) which are beginning to set the basis for more successful future shoreline management.

There are many problems yet to be resolved. In terms of coastal hazards, the main points to be borne in mind are that natural coastal processes are no respectors of legal definitions or administrative boundaries; that while segmentation of coastlines is necessary for planning purposes, this segmentation should be based on natural coastal process systems or "cells"; that protective measures need to take into account long-term trends (such as rising sea levels) as well as immediate threats; and that there is a fundamental need for cooperation in coastal management among natural scientists, engineers, administrators, politicians, and coastal users and owners (Clark, 1974, 1978). The value of coastal land and property at risk is immense and will undoubtedly increase as sea levels rise. The numbers of people at risk are probably of the order of half a million, and also rising as more and more people move to coastal areas for retirement. Insurance companies are becoming seriously aware of these increasing risk factors, and premiums are already showing sharp rises.

6. Soil erosion

Danger from soil erosion in Britain is comparatively low but by no means absent. Sometimes after severe rain storms, loss of soil from arable fields, especially where the soils are sandy or loamy, can be detected from the signs of rilling and accumulation of sediment at the bottom of sloping fields, but deep gullying is unusual on cultivated land. Strong winds can sometimes raise clouds of dust from the peat lowlands or light soils in the drier climates of eastern Britain, but there are few data on the long-term implications of such processes. The frequency of erosion events also needs much more research, but data in part of southern England suggest that those fields which erode do so, on average, about once every 5 years under present climatic and land-use conditions (Boardman, 1990). Soil erosion in general is now far less than during early Man's first clearance of the land for agriculture around the Bronze Age.

Table 8.7, after Morgan (1985), shows the regions of present-day risk and some mean annual rates of soil loss, based on limited data. Little is known about current rates of soil formation, which in any case will differ from one soil type and one region to another, but a figure of 1 t/ha/year may indicate the order of magnitude. The threat of soil erosion is therefore insidious; usually not apparent to the eye, depletion of the soil stock over time may be serious in some areas.

Water erosion comprises three main processes: raindrop splash detachment, overland sheet flow and rilling. Recent work has suggested that splash is a relatively unimportant agent of transport, and that overland flow is much less important than rilling which is the dominant transporting process. Erosion by water is linked to four main groups of factors: ground surface characteristics (slope angle, micro-relief and roughness, infiltration capacity at the surface, erodibility), rainfall characteristics (volume and intensity), soil characteristics (texture, structure, infiltration capacity, antecedent moisture) and type of crop cover, including its variations through the growing season.

Although it is usual to think of soil erosion as occurring mainly on steeper slopes, recent work has shown that this is not always the case. Rilling has been noted on slopes as low as 3 degrees. Evans (1990) found that, in seventeen localities spread through England and Wales, one-third of all forms of erosion in a 3-year period occurred on valley floors, sometimes taking the form of a broad shallow-cut swathe down the valley

Table 8.7. Areas of soil erosion risk and conjectural rates of soil erosion in Britain. *Source*: R.P.C.Morgan, 1985

Areas affected	Conjectural erosion rates (t/ha/yr)
Water and wind erosion on arable land: 3400km^2; Vale of York, Nottinghamshire, north Norfolk	195 (gullying) 21-44 (wind)
Water erosion on arable land: 10 800km^2; Midlands to southern England	10-30
Wind erosion on arable land: 3600km^2; mainly eastern England	No data
Wind erosion on lowland arable peatlands: 2700km^2; Fens, west Lancashire, Somerset	No data
Water erosion on upland non-cultivated peat soils: 5000km^2; Highlands of western and northern Britain	10-30
Wind erosion of coastal sands and sand dunes	No data

centre and sometimes incised by a deeper rill or gully. Micro-relief and surface roughness on arable land are strongly affected by type or stage of cultivation: newly ploughed land, for instance, rarely erodes, but fields become very susceptible to damage when the surface has been rolled and compacted prior to seeding. Direction of ploughing is another related consideration. Intense rainfall has often been considered a prerequisite for soil erosion, but in Britain rainfall energy is in general low (Morgan, 1980), and studies have shown that prior saturation of the soil is just as important a factor. Even a fall of just 10mm has then been observed to cause erosion (Reed, 1979); Reed also noted that runoff and erosion can occur on saturated soils at an intensity of just 1mm an hour. Crop cover is an important control. Most soils only erode when they are bare or the amount of ground cover is less than 10 per cent. In this connection, certain crops provide less ground protection than others. The spread of maize cultivation in parts of south-east England has exposed some fields to overland flow and surface rilling which were not previously a problem.

Because of the complex interplay of these various factors and the difficulties in quantifying some of them (e.g. soil structure), there has been little success so far in modelling erosion risk, though Morgan (1985) has published a tentative map of areas of soil erosion risk. This utilises knowledge of the general erodibility of the main soil associations, potential rainfall intensities and limitations of land capability. The six categories of risk given in Table 8.7 are derived from this map.

Wind erosion has received less attention apart from a few areas and particular storm events (e.g. Radley and Simms, 1967; Robinson, 1968). Morgan (1985) suggests that, for the whole country, wind speeds are likely to exceed a threshold level of 34km/hour (at

10m above the ground) at least once a year, but effects will only be significant in areas of sensitive soils, mainly sandy loams and clay loams with low organic content, unprotected by crops at the time and following a period of dry weather.

In conclusion, soil erosion in Britain is most of a risk on sandy or sandy loam soils, with slopes steeper than 3 degrees and where the land is under arable cultivation. In the worst conditions, serious soil erosion can even be an annual event. Altogether, Morgan (1985) considers that as much as 37 per cent of the total arable area of England and Wales is at risk; a further 6 per cent comprising non-arable land may also be in danger.

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GREECE

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1. Introduction

With its striking relief patterns of high-ranging mountains and deep valleys, rapid changes of surface form, a close juxtaposition of land and sea, an intricate coastline and a varied and complex geological structure, the physiography of Greece is amongst the most distinctive in Europe. A series of mountain chains extends roughly from north-west to south-east, fingering out into a series of peninsulas and islands. In the Aegean, the trend, expressing the Alpine tectonic imprint (Fig.9.1), curves to adopt a more east-west alignment. Many ranges exceed 2000m; Mt Olympus touches 2917m. In contrast to the Alps, few parts were glaciated, the glaciers of the late Pleistocene nowhere descending below about 1000m.

Separating the mountain ranges are numerous basins and valleys, often flat-floored and sharply demarcated, and traversed by rivers of which the longest, in the north-east, rise outside the borders of Greece in former Yugoslavia or Bulgaria. The longest river wholly within Greece is the Aliakmon with a length of 297km. Many rivers are ephemeral, dry in summer but becoming raging torrents for short times in winter. Others fed by karst sources show a more constant discharge.

Structurally, there are two principal domains: the Aegean tectonic plate, mostly submerged by the sea, and the folded mountain systems of the Hellenides which continue north-westwards into Albania as the Dinarides and eastwards into Turkey as the Taurides. Parallel to and outside the Hellenides are the various island arcs of the Ionian Sea, Crete and other islands, flanked by deep-sea trenches in which the greatest depths of the Mediterranean are found - 5015m only 50km offshore from Akra Taínaron. In the Aegean area, the predominant rock types are crystalline and metamorphic, of Palaeozoic age; the Hellenide ranges comprise primarily Mesozoic limestones flanked by Tertiary flysch and other sediments. Major fracture systems separate mountains from basins; vertical movements are still active, in which the basins are areas of tectonic subsidence, the mountains showing uplift in contrast.

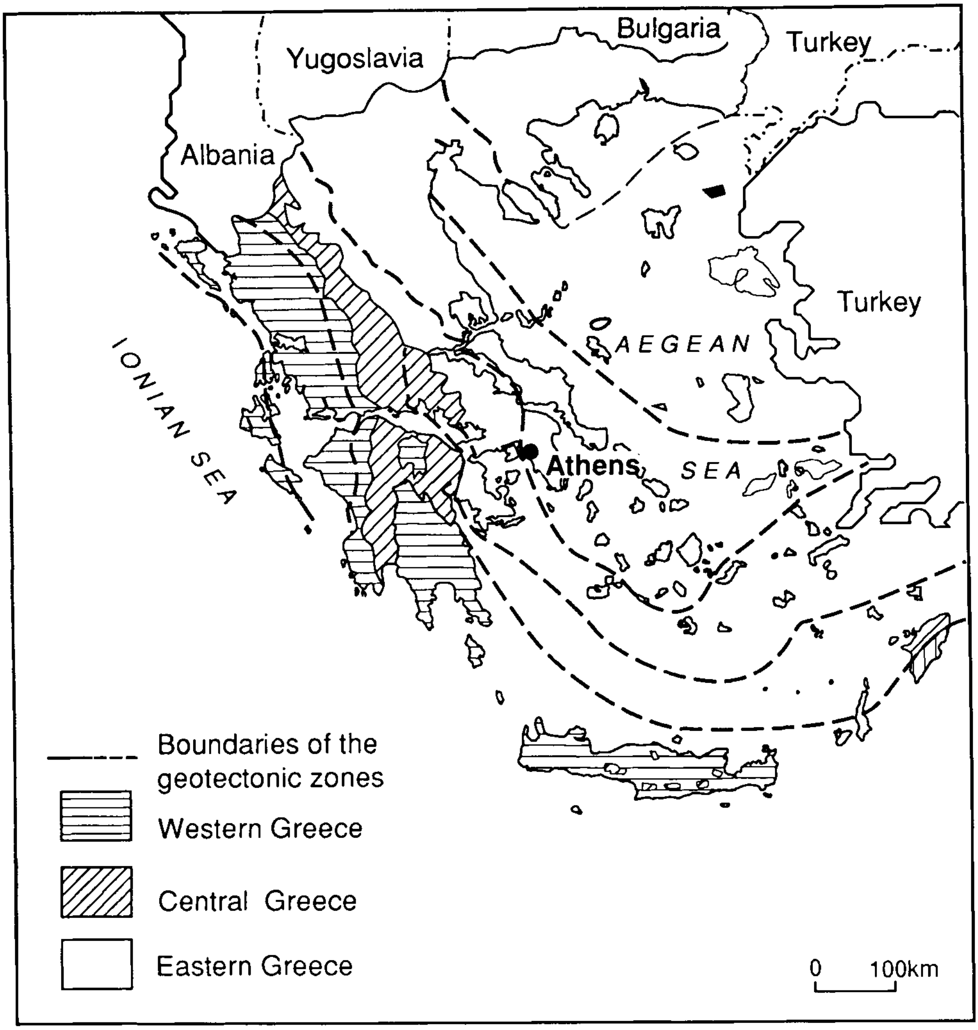


Fig.9.1. Geotectonic zones of Greece (Koukis, 1982)

The typical characteristics of the Mediterranean climate dominate the country. Precipitation is highest in western Greece, exceeding 1800mm on the high mountains of the Pindos and also in western Crete, but declines rapidly eastwards and south-eastwards to less than 300mm in the eastern Aegean (Karapiperis, 1974; Karras, 1973). Concentrated in the winter season, the precipitation is also characterised by the occurrence of occasional intense rainfall events, and by great variability from year to year. In contrast to other Mediterranean areas, the frequency of thunderstorms is low.

The months of November to April can bring snow to the mountains and sometimes even to lower areas; snow is much more frequent in the north of the country but skiing is still possible until April on Mt Olympus.

In this country of some 10 million inhabitants, the impact of geomorphological hazards varies from the sudden and catastrophic, such as earthquakes and landslides, to the more predictable risks of periodic winter flooding in some lowland areas, and the long-term and largely irreversible dangers of slow soil erosion.

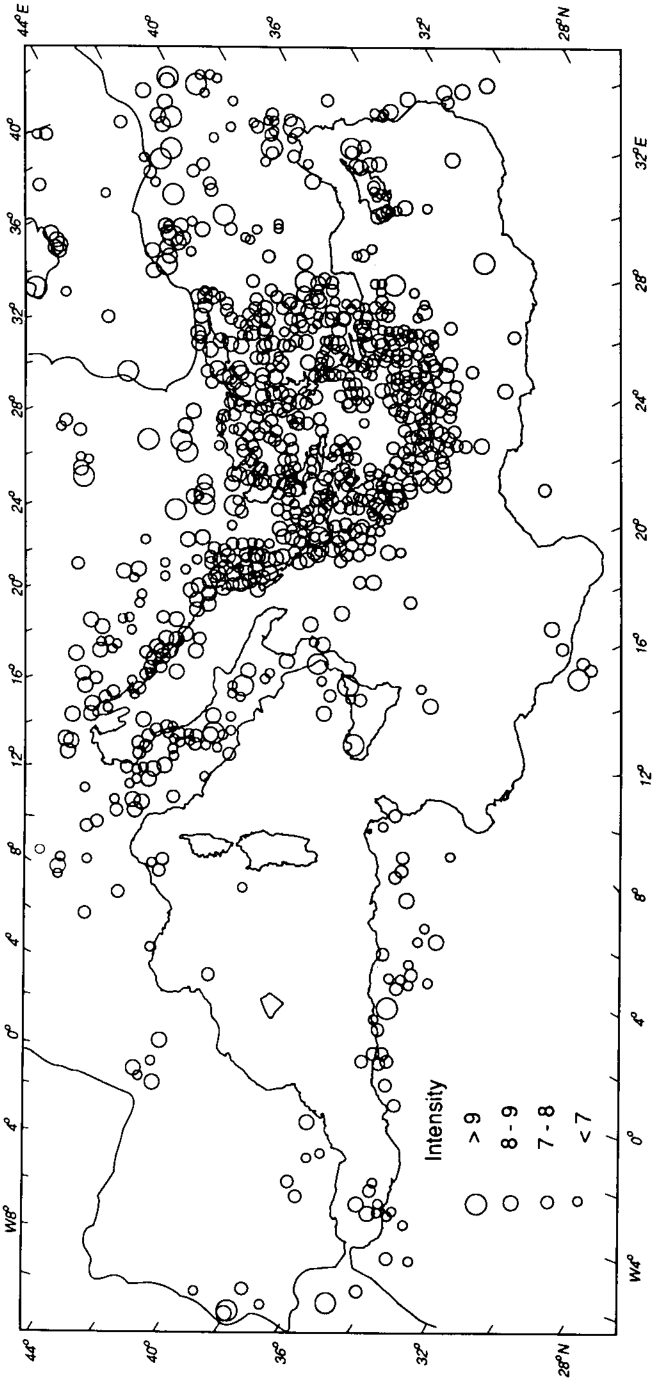
2. Seismic activity

The country is undoubtedly the most seismically active in Europe, with a long recorded history of disastrous earthquakes (Fig.9.2; Koukis, 1988b). This arises from its situation in the eastern Mediterranean where a mosaic of microplates have been in motion for the past 200 million years and still continue to adjust their relative positions. Many of the fault systems that are seismically active today have been active since at least the early Pliocene. Basically, most of Greece belongs to the Aegean plate (strictly, tectonic domain) which is being underthrust from the south and south-west by the Ionian plate, a part of the Mediterranean lithosphere. The present margin between the two is marked by the Hellenic deep-sea trench and the parallel island arcs represented by the Ionian Islands, Crete, Kárpáthos and Rhodes (Mercier *et al.*, 1979). This subduction zone, where the rate of convergence is between 2cm/year in the west and 5cm/year in the east, is characterised by frequent and sometimes devastating earthquakes (Drakopoulos and Makropoulos, 1983; Makropoulos and Burton, 1984), making it by far the most seismically active zone of the whole of Europe and North Africa. The deep-focus character of many of the earthquakes here was recognised long ago in the 1920s. The highest activity is at the southern end of the Ionian arc (Kefallinía, Zákinthos) where epicentral intensities can reach X (MSK scale) (Fig.9.3) and, in the east, parts of Crete, Kos and Rhodes (intensities reaching VIII or IX). The subcrustal seismicity shows that the subducted slab dips gently towards the north-east for the first 200km, but more steeply beneath the Gulf of Argolis in the east of the Peloponnese. The direction of subduction is probably not simply perpendicular to the trench but involves an oblique component.

Another tectonically and seismically active zone is represented by the Gulf of Corinth (Vita-Finzi and King, 1985). This is an active graben in a zone of extensional stresses since the middle Pleistocene. Neotectonic movements are here mostly along east-west trending normal faults (Mariolakos, 1979). Epicentral intensities of some recent earthquakes have reached VIII, IX or more (Fig.9.3).

In the north of Greece, a further area of strong epicentral intensities lies around and to the south-east of Thessaloniki (VIII-IX).

Among the disastrous events of the historical past was the destruction of Sparta in 464 BC, when perhaps 20 000 persons were killed, the complete annihilation of the thriving city of Elike, east of Aegion, in 373 BC (Koukis, 1988b), and the catastrophic earthquake of Olympia in 6 AD. Other major earthquakes in more recent times have


Intensity
> 9
8 - 9
7 - 8
< 7
44°E
40°
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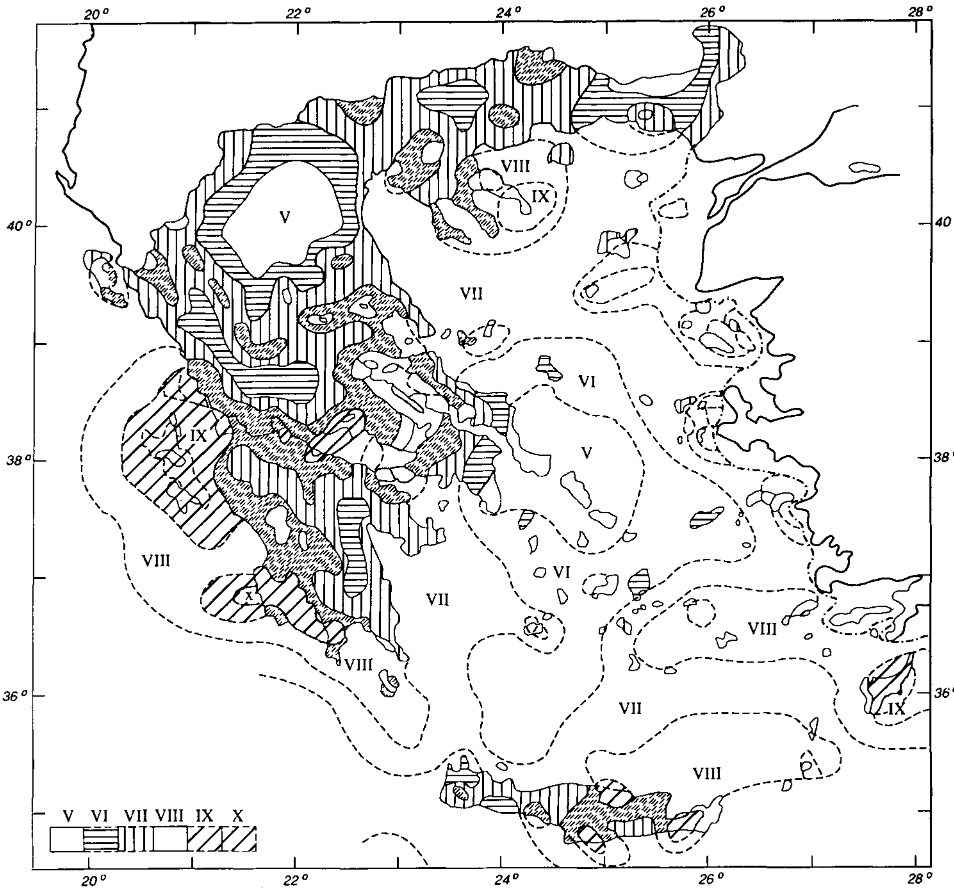

Fig.9.3. Generalised map of maximum observed epicentral intensities in Greece, 1700-1981 (Drakopoulos and Makropoulos, 1983)

included those of Crete (1856), the earthquake series of 1886-87 in Messinia (south-west Peloponnese) which destroyed three towns and 123 villages, Rhodes (1926, M = 8.2), the Ionian Islands (1953: M = 7, with severe destruction on Zákinthos), Salonika (1978), the earthquake series around Corinth in 1981 (King *et al.*, 1985; destruction of Loutráki and damage in Athens), and Kalamata (1986: southern Peloponnese).

In contrast to the areas of exceptional seismicity, it should be noted that there are also parts of Greece that are relatively immune from earthquakes (Fig.9.3). These include a large part of the Aegean block, north-eastern Greece and Thrace, extending into southern Bulgaria, and the northern part of central Greece.

Fig.9.2. (*facing page*) Distribution of earthquake epicentres in Greece (Koukis, 1988b)

3. Tsunamis

It is likely that a sizeable tsunami resulted from the explosion of Santorini in about 3450 BP, when the central area of this volcanic island, some 80km^2, collapsed to leave a caldera 300-400m deep (Galanopoulos, 1960). The cavity formed by the explosion was about four times greater than that of Krakatoa, and caused the generation of tsunami waves which destroyed most Minoan settlements on the north and east coasts of Crete. It is estimated, however, that the tsunami did not exceed 7-8m, possibly because of the great depths and gentle slope of the sea floor north of Crete.

Galanopoulos (1960) lists 41 other known tsunamis that have affected the coasts of Greece between 479 BC and 1956 AD. In the last three centuries, data on maximum wave heights become more reliable, for example:

1650 AD Waves up to 16m on Ios, possibly higher on Patmos, following a submarine earthquake near Santorini.

1861 AD A strong earthquake in the Gulf of Corinth, followed by five tsunamis which reached 15-60m, inland from the north coast.

1886 AD An earthquake on the west coast of Messinia (Peloponnese) resulted in a tsunami which was recorded as far away as Smyrna; near Agrili, the sea rose to 10-15m.

1956 AD The earthquake in the Cyclades, centred near the island of Amorgos, M=7.8, produced waves with reported heights of 20-25m.

By no means are all earthquakes accompanied by tsunamis. For earthquakes with epicentral intensities greater than VIII, Galanopoulos (1960) estimates that only one in about 20 or 25 have given rise to damaging tsunamis in historical time; and that this proportion does not constitute such a serious danger that a warning service should be established. He also suggests that some of the tsunami are generated not by the earthquake direct but by the sliding of unconsolidated submarine sediments.

4. Volcanic activity

A typical feature of subduction zones is the presence of a volcanic arc over the subducting slab. Such an arc is present in the Aegean region, consisting of a series of Pleistocene and Holocene volcanic centres including, among others, the islands of Santorini, Milos and Aegina.

Today, the only active volcanism is to be found on Santorini: specifically, the volcanic island of Kaimeni located in the flooded caldera (Fig.9.4). Outbreaks this century, producing dacite lavas and tuffs, have occurred in 1925-28, 1939-40, 1950 and 1956, but present no real hazard because of the isolated situation. On the other hand, the cataclysm of about 1470 BC has become famous for its supposed extensive destruction. The event was comparable in magnitude to the explosion of Krakatoa (1883), and has been said by some to have caused the collapse of the Minoan civilisation, apart from the great damage certainly brought to Minoan settlements. The tale of the disappearance of Atlantis, dated by archaeologists to the Bronze Age, is probably related to this

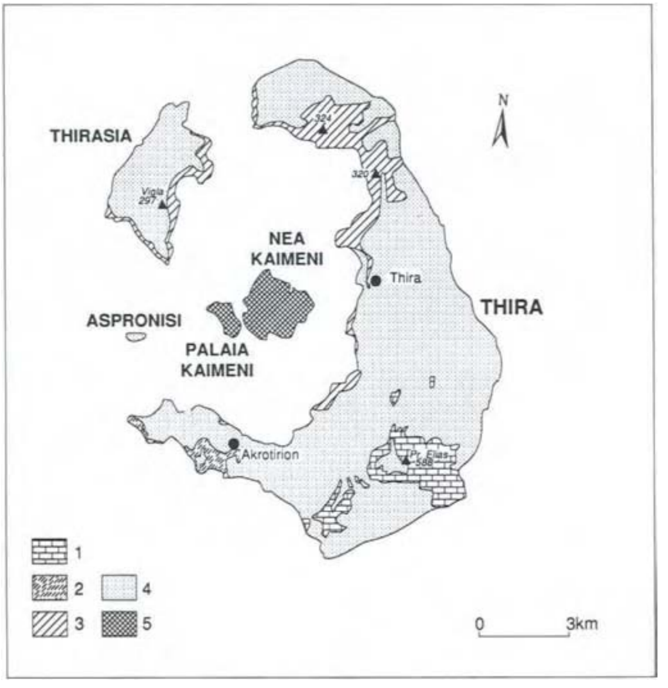

Fig.9.4. Geological map of the island of Santorini (after H.Pichler *et al.*, 1972) 1. Triassic reef limestones and Tertiary phyllites of the sedimentary basement; 2. Acid pumice tuffs and dacite lavas of the oldest (Pleistocene) eruptions; 3. Andesitic, basic lavas and pyroclastic facies produced by prehistoric volcanic activity; 4. Rhyodacitic pumice-beds of the last great eruption (1470 BC); 5. Young dacite lavas and tuffs of the Kaimeni islands.

geological event. However, the facts that the thickness of the ash layer in eastern and central Crete is not more than about 5mm, and that the associated tsunami, as already mentioned, was not particularly large, hardly seem of sufficient magnitude to wipe out a whole civilisation; archaeologists are now more inclined to the view that other factors had already caused a decline in the economy and society, and that the eruption was merely one more blow.

5. Mass movements

With its diversity of lithology, complex structure and strong tectonic fracturing, Greece is a country where landslides are frequent and pose serious problems for the population and the economy (Koukis, 1982). In western and central Greece, many factors combine to promote slope instability - strong relief, lithology, neotectonics, seismicity and occasional heavy rainfall (Andronopoulos, 1982). On the other hand, eastern Greece exhibits more stable conditions since this part consists mostly of compact and cohesive metamorphic rocks, is characterised by less intensive tectonics, and receives less rainfall.

The landslide problem in Greece has many aspects - technical, economic and social - and landslides pose serious threats in places to engineering works, transport lines, and even the viability of whole areas. As an illustration of the scale of the problem, no less than 500 villages have had to be re-sited during the last four decades.

A great number of landslides are essentially local phenomena. Figure 9.5 shows the general landslide distribution. The most serious landslides occur in central Greece, in the Olonos-Pindos zone, comprising thin-bedded Upper Cretaceous limestones, the transition to the flysch, and the flysch itself. These formations are highly folded and fractured, disposed in alternating layers of different mechanical properties, each showing a characteristic plasticity and flexibility. These unstable formations occur particularly in areas with steep slopes, affected by strong deformation stresses in the past and, in some areas, being affected by additional neotectonic stresses, as around the Gulf of Corinth. In this province, the landslides are thus connected with the release of

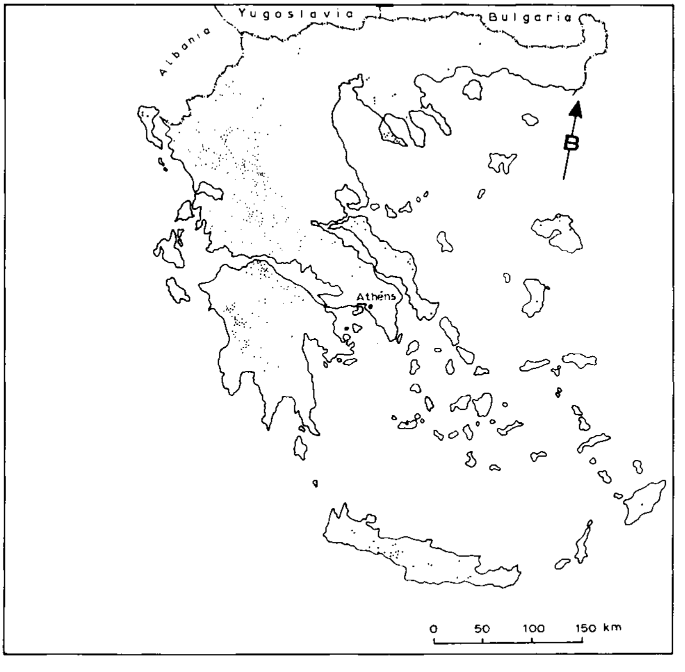

Fig.9.5. Distribution of landslides in Greece (Koukis and Ziourkas, 1991, p.51)

residual and neotectonic stresses, while in the less tectonically-disturbed areas, mass movements are more related to local morphological, hydrological and hydro-geological conditions, and the immediate causes tend to be meteorological, seismic and related to human activities.

5.1. Geological controls on landsliding

The geological formations of Greece may be grouped as follows, according to their engineering geological characteristics (Koukis, 1988a):

5.1.1. Quaternary deposits These comprise basin infills, slope deposits and alluvial tracts. Since a large part of the population lives in the alluvial basins and lowlands, these materials also form the foundations for many engineering structures and are therefore very significant in terms of potential hazard (Fig.9.6). Their properties are extremely variable, both horizontally and vertically, and some formations contain swelling clay minerals.

5.1.2. Neogene sediments and molasse. Three types are differentiated from an engineering viewpoint - fine, coarse and mixed - which determine their mechanical behaviour. Generally, they have low density and strength, and may show both swelling and shrinkage phenomena. Rock falls and slides prevail in the coarse sediments, earth flows, creep and rotational failures in the fine sediments (Fig.9.7).

Fig.9.6. Progressive rotational slides in alluvial deposits, Evros river area, north-eastern Greece

Fig.9.7.A (*upper*): Rotational slides in marly Neogene sediments, transformed into earthflows near the foot which abut on the Preveza-Igoumenitsa road, western Greece. B (*lower*): Collapsed house built on clayey-marly Neogene sediments

5.1.3. Flysch covers extensive areas in western Greece and exhibits a high frequency of landslides. It consists of argillaceous shales, siltstones, sandstones and conglomerates. Much of its outcrop corresponds to areas of strong relief and relatively high rainfall. Mass movements, especially translational and rotational slides (Fig.9.9), earth flows, creep and, to a lesser extent, rock falls are frequent. Most of the failures occur where the flysch is highly fractured or weathered (Fig.9.8); elsewhere it can be relatively stable.

5.1.4. Limestone, dolomite, marble and schist-chert. Apart from the last, these are hard rocks with considerable static and dynamic stability, even though they occupy areas of intense relief and have been strongly affected by tectonics. Where, however, they have been thrust over younger formations, especially flysch, highly unstable conditions are

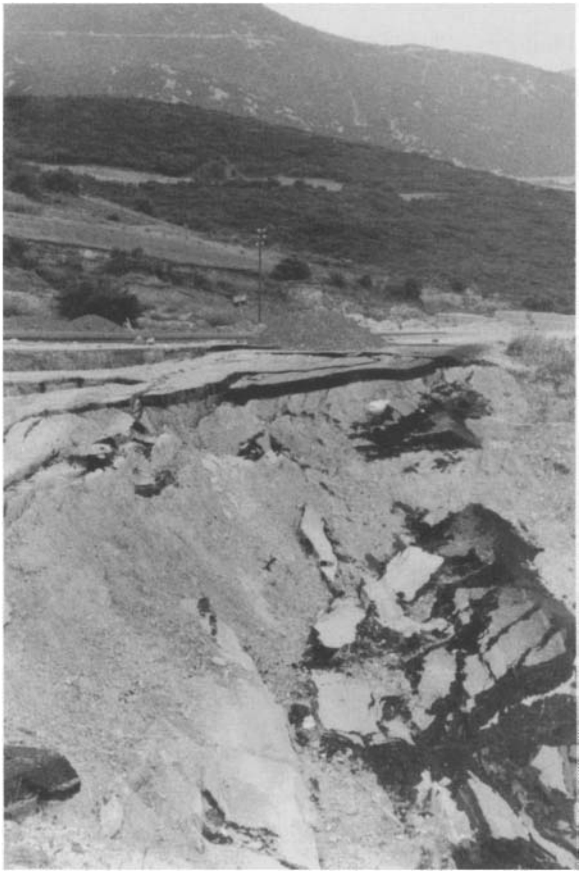

Fig.9.8. Failure of road embankment with poor foundations on weathered flysch and lacking drainage

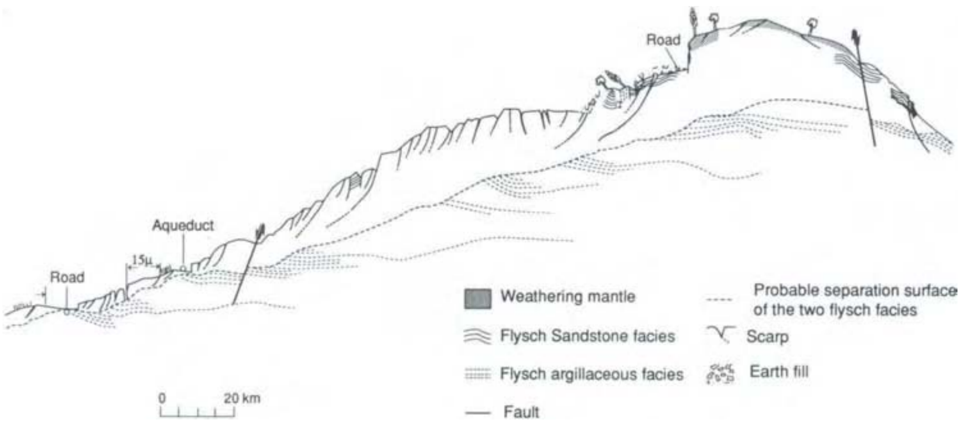

Fig.9.9. Rotational failures in flysch, in which a sandstone facies overlies an argillaceous facies (Koukis, 1988a, Fig.3)

present, with major rock falls and slides (Fig.9.10). The schist-chert comprises highly fractured alternations of siltstone, sandstone and limestone, readily failing in slides and falls in areas of strong relief; their weathered mantles also show creep and earthflows.

5.1.5. Cipoline, schist, phyllite and gneiss occupy extensive areas in eastern Greece. They are high density rocks with high compressional and tensile strengths, but where fractured, strongly bedded and located in areas of strong relief, they can nevertheless fail as translational slides and falls. Their weathered mantles also exhibit creep and flow phenomena.

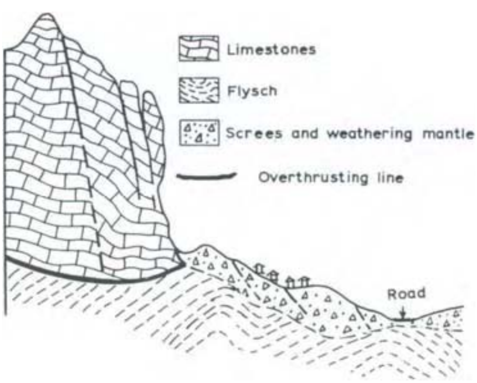

Fig.9.10. Massive limestone overthrust on flysch, a situation that threatens many villages and roads in central Greece with rock falls and slides (Koukis, 1988a, Fig.5)

5.1.6. Ophiolite and granite show satisfactory strength. It is only where slopes are steep and there is a sufficient degree of fracturing or foliation that rock falls occur.

5.1.7. Volcanic rocks are present in a variety of forms from solid to friable, but are in general mechanically strong. Mass movements are generally in the form of rock falls.

5.2. Frequency distribution of mass movements in relation to lithology

Table 9.1 shows the relative frequency distribution of landslides in the principal lithological groups, based on 802 cases examined (Koukis and Ziourkas, 1991). The highest frequencies are recorded on flysch (over 35 per cent) and on Neogene-molasse sediments (over 30 per cent). If the area covered by each of these formations is also taken into account, the relative frequency for flysch landslides rises to 42.8 per cent. In terms of structure, 40 per cent of a sample of 384 landslides show strata dipping towards the landslide face. The influence of climate is shown by the fact that the relative frequency of landslides rises to over 62 per cent in areas with more than 1400mm of precipitation; the cumulative figure for areas with over 1000mm is nearly 77 per cent. Most landslides first appear or become reactivated in winter (*c.* 80 per cent) or spring (10-15 per cent).

5.3. Analysis of the immediate causes of landsliding

Based on data from the sample of 802 landslides, the following causes were identified as most important:

- earthquakes
- basal undercutting by rivers or coastal erosion
- subaerial weathering, including frost, wetting/drying
- groundwater conditions
- physico-chemical changes in clays
- gross geological structure and slope geometry
- precipitation events
- artificial disturbance by excavation

Factors contributing to low or reduced shear strength appear on the whole to be significantly more important than factors causing increased shear stress, though there are exceptions. Physico-chemical changes in clays (softening of fissured clays, swelling, hydration of clay minerals, base exchange and migration of water to the weathering front under electrical potential) appear to be the primary cause in about 22 per cent of all cases. Reactivation of existing landslides is apparent in 45 per cent of the cases examined; while 18 per cent show two known reactivations.

5.4. Hazard assessment and protective measures

Regional differences in the overall level of risk as between eastern Greece on the one hand, and west-central Greece on the other, have already been noted. In eastern

Table 9.1. Frequency distribution of landslides in different lithological formations (Koukis and Ziourkas, 1991)

Formation	Frequency of landslides (per cent)	Area of landslides (per cent)	Relative frequency of landslides
Quaternary	16.2	15.9	0.104
Neogene & molasse	30.2	24.0	0.128
Flysch	35.6	8.5	0.428
Transition zone to the flysch (cherts, schist-cherts, etc.)	3.0	1.2	0.250
Limestone	3.6	19.5	0.019
Phyllite-schist	8.6	18.4	0.048
Volcanic	2.7	12.6	0.022
Totals	99.9	100.1	0.999

Greece, where there are more stable geotectonic conditions and more compact and cohesive rocks in general, landslides are mainly limited to the Neogene sediments and loose Quaternary deposits. Many of the villages in this region are located at the bases of steep hard-rock slopes, where rock fracturing leading to rock falls is the main hazard. The same applies to roads located in such positions. While such rock falls are relatively rare, their prevention or prediction are often difficult and/or expensive. The following measures are most commonly undertaken in such situations:

- removal of loosened blocks and lowering the slope angle by re-grading;
- sealing of cracks, covering weathered slopes with shotcrete, and diversion of surface water away from the slope by construction of trenches at the head;
- construction of retaining walls (often employing gabions) and buttresses;
- minor works such as planting of deep-rooted trees and covering loose slope material with anchored wire mesh.

In western and central Greece, a distinction should be made between shallow mass movement phenomena and the larger, more serious landslides (Fig.9.11). Some state-financed geotechnical mapping has been undertaken at scales between 1:5000 and 1:20 000. The first approach is review the incidence of known mass movements, the hydro-geological conditions, and potential or known causes of movement. The measures adopted in the case of shallow failures are similar to those described above for eastern Greece. A combination of measures is usually called for but not often implemented; it is often also the case that expensive or elaborate works are undertaken when simpler measures might have been just as or more effective; and there is a need for better coordination among the various official departments concerned and scientists involved.

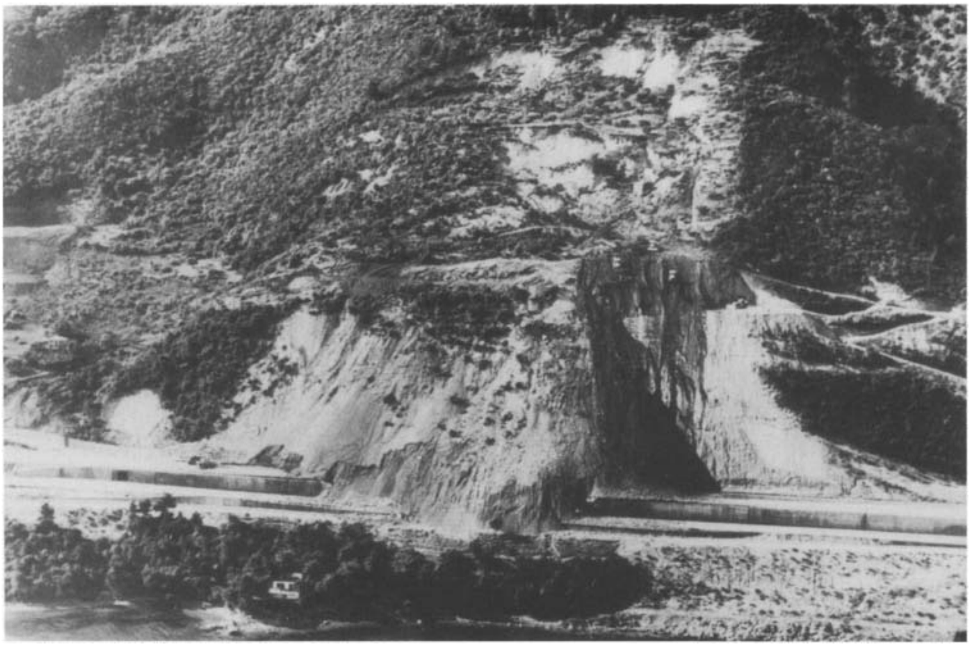

Fig.9.11. General view of the extensive landslide developed in thin-bedded Upper Cretaceous limestones and the transition zone to the flysch: Athens-Patras national road, Gulf of Corinth (Olonos-Pindos geotectonic zone). Scale is given by the house, lower left, and the three bulldozers working on the debris, right centre

In the case of more serious landslides, evacuation of whole villages and their re-siting has sometimes been necessary. Until the mid-1970s, the State prompted some re-siting of settlements even outside the area to which they belonged socially, with the aim of consolidating some of the upland settlements to create larger inhabited units, mainly in agricultural areas. Such attempts have generally failed, because people used a new house without abandoning the old one. Nevertheless, the programme succeeded in re-siting some 500 out of 9000 villages. The problem today is tackled in a different way, and is based on technical improvements to the foundations of buildings and improved construction techniques. It is more common now to advise relocation within an existing settlement to avoid a particular danger.

In the country overall, and based on the sample of 802 landslides referred to previously, the following hazard mitigation measures are most often employed:

1) Re-siting of buildings or occasionally whole settlements (20 per cent)
2) Surface and sub-surface drainage (29 per cent)
3) Retaining walls and structures, either of concrete or gabions (13 per cent)

4) Tree planting (11 per cent)
5) Barrages (9 per cent)
6) Benches (4 per cent)
Percentages represent the approximate frequency with which the proposed measures are invoked.

6. Soil erosion

Under present climatic conditions, soil-forming processes are exceptionally slow. It has been argued that many soils are in fact fossil soils, and that once destroyed, regeneration is unlikely or at least a very long-term process. This fact highlights the seriousness of the widespread and long-continued loss of soil by human-induced erosion.

It is known that soil erosion in Greece was already advanced in Minoan times, and was intensified during the Greek and Roman eras. Perhaps its origins may be traced to climatic changes around 5000-6000 BC, though ever since man began to clear the forest, the soil has been at risk. The hot dry summers, the occasional torrential winter rains, and the prevalence of limestone, mean that any form of destruction of the vegetation on slopes will have disastrous consequences for the soil. Clearance of land for agriculture, cutting of the forest for timber, and above all the introduction of vast herds of grazing animals, have meant that, today, only 18 per cent of the country is classified as woodland, even including the light woodland of the macchia. Sheep and goats now number some 13 million, more than the human population of Greece, and effectively prevent forest regeneration in areas where they roam freely. Another adverse factor is forest fire which causes exceptional damage: in 1985, for instance, the greater part of the forest on the island of Thasos was destroyed by fire. Finally, there has been the growth of population placing ever greater demands on the remaining forest, and the emigration of people out of the mountains where the old terraces and soil and water conservation systems have been allowed to decay. The result is only too obvious: unprotected hillsides have been stripped bare of soil, and those where soil still remains are suffering severe erosion, visually obvious in the red-brown colour of the river water during winter rains.

7. The flood hazard

The Greek myth of Hercules fighting against Acheloos epitomises the struggle of the early Greeks against the destructive power of floods. Acheloos, the river with the highest mean flow rate, was worshipped as a god by the ancient Greeks. As depicted on Greek vases, Acheloos was metamorphosed into a snake and then into a bull, but was finally defeated by Hercules who won Deianira as his wife. According to the historian Diodorus and the geographer Strabo, the meaning of Hercules' victory is related to the successful building of dykes to confine the shifting channel of the river Acheloos. No technical descriptions of these early engineering works survive, only some presumed remnants of the dykes (Constantinidis, 1993, p.1). From Strabo, it is known that similar structures had also been built to control another large river, the Pinios at Larissa on the Thessalia plain (Constantinidis, *ibid.*, p.26).

7.1. Causes, magnitude and geographical distribution of floods

Floods in Greece usually arise from intense rainstorms: snowmelt is not a main factor in flood genesis. Most intense rainstorms are produced by the passage of depressions, possibly accompanied by cold fronts (rarely warm fronts) approaching from the west, south-west or north-west. Heavy rain of convectional origin, associated with a cold upper air mass that produces dynamic instability, is another important contributor to flooding, especially in summer (Maheras, 1982; Mamassis and Koutsoyiannis, 1993).

Orographic factors play a major role in determining storm and flood intensity. The maximum 24-hour rainfall depth for a 50-year return period can be used as a rough indicator of flood severity, although a 24-hour period is too long if compared with the travel times of flood waves in Greek catchments. This rainfall-depth index is as much as 175mm in the Pindos Mountains of western Greece, but to the east of these ranges it falls to 100mm, before rising again to 175mm in the East Aegean islands (Flokas and Bloutsos, 1980). This does not, however, mean that floods in the relatively dry east of Greece are uncommon. Whereas the mean annual rainfall exceeds 1800mm in the mountains of western Greece, it drops to 300mm in the eastern regions of the country. Thus, the reduction of the maximum 24-hour depth from west to east (175 to 100mm) is not nearly so rapid as the reduction in mean annual rainfall.

Flood magnitude, measured by the peak flow or total volume, is directly related to drainage basin area. Using a 30-year record, Mimikou (1984) has analysed flood data from six rivers in western and north-western Greece. She determined the envelope curves (Fig.9.12) relating maximum observed flood-peak discharge to drainage basin area. As the regression lines in Figure 9.12 show, the relationship appears to be a power function.

Deforestation and urbanisation play a further important role in flood generation, and are likely to be responsible for the increasing severity and destructiveness of floods, especially in recent times but also earlier. Deforestation, with soil erosion as its consequence, is a major problem in Greece (see section 6). The extent of forest-covered areas today is only 18 per cent of the area of Greece, whereas at the beginning of the nineteenth century it exceeded 40 per cent. Deforestation has been mainly caused by human activities such as burning, illegal land reclamation and the pasturing of sheep and goats (Kotoulas, 1980).

7.2. Floods in mountainous areas

The striking relief patterns, the long and intricate coastline, and the abundance of islands, have led to the formation of numerous small (tens to hundreds of km^2) and steep drainage basins. Such basins characterise the mountainous and hilly areas which

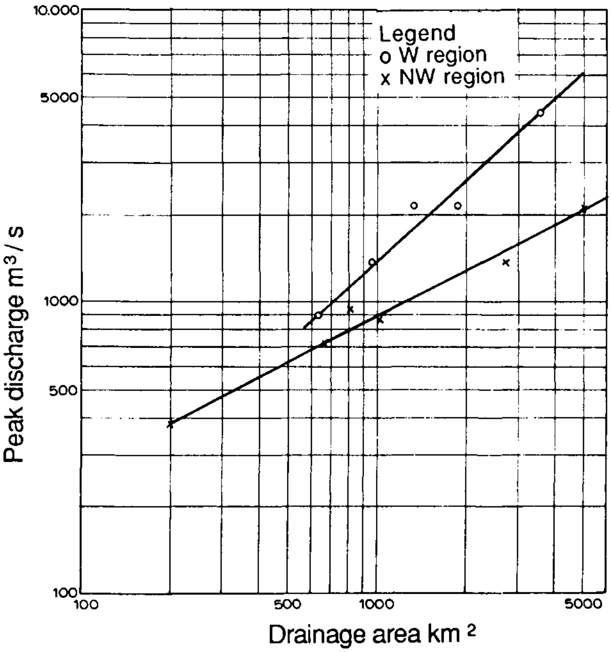

Fig.9.12. Envelope curves of peak discharge versus drainage basin area for a series of rivers in western and north-western Greece (after Mimikou, 1984)

make up some 65 per cent of Greece, leading to steep channel gradients and deep confined valleys. As a result, floods are usually routed without disastrous impacts. Sometimes, however, the channel banks may be overtopped, causing damage to nearby buildings and roads. In such a situation, loss of human life can be a real risk because of the very rapid propagation of such flash floods. For example, six people recently (24 August 1990) lost their lives from the overflow of a small stream in Vassilika, Evia, 70km to the north of Chalkis.

Flood hazards in the mountains are strongly associated with soil erosion and the destruction of agricultural land. Heavy sediment transport and mass movements are typical consequences. The author recalls from his childhood (c.1967) a devastating combination of flooding and landsliding in a tributary valley of the Acheloos river, at his village of Messounta (province of Epirus) in the Pindos zone of north-western Greece. For more than a week, the stream carried a thick mixture of water, soil and rock debris which had entered the stream as a result of a landslide. The viscous flow reached a depth of 6-7m, breaking a concrete bridge 20m long and carrying it as a floating object for about 500m downstream. In spite of the apparently threatening aspect of this event, the frightening noise accompanying it and its long duration, no other damage was caused apart from some loss of land and the effect of the landslide itself. The deep valley and the steep banks enclosing the stream channel prevented the flood from expanding.

7.3. Closed hydrological basins in karst areas

The existence of closed hydrological basins surrounded by mountains of limestone and drained by natural sinkholes is not uncommon in Greece. The lowest part of such basins consists of a plain, and a permanent or ephemeral lake is usually formed. Such basins are very sensitive to flooding because of the limited drainage capacity provided by the sinkholes.

An interesting example of such a situation is the Boeotic Kifissos basin, with an area of about 2000km^2 and no surface escape for drainage. It is located in the east-central part of Greece, not far from Athens, and receives the Boeotic Kifissos river with a length of about 100km, whose network extends to altitudes of 2400m. The plain in the centre of the basin has an area of about 250km^2 and stands at an elevation of 95m. Prior to 1900, much of the plain was permanently flooded by the river, forming the shallow lake Kopais with an area of about 150km^2. During years with high flows, however, the lake expanded to 250km^2 because the capacity of the sinkholes was insufficient. Attempts to ameliorate the situation were initiated in ancient times, as reported by the geographer Strabo, but did not succeed. The problem was only remedied at the end of the last century by construction of a tunnel to take the flow of the Boeotic Kifissos to the external lake Iliki. In addition, a broad network of canals, drains and levees was built in the plain. Recently, a new tunnel with a discharge capacity of 590m^3/s (in addition to the 160m^3/s of the old tunnel) improved the situation (Constantinidis, 1984). However, the flood problem of the region is not yet fully solved. The discharge capacity of the system at various locations along the river network is insufficient for the more severe flood events, thus causing inundation of agricultural land. Moreover, owing to the design philosophy that gave priority to protecting the plain of the former lake Kopais, various hydraulic works were constructed in the upper and middle course of the Kifissos to provide temporary flood storage, but these have unfortunately exacerbated the flood risk upstream. A minimum of 10km^2 of agricultural land in the upper and middle reaches is flooded each year, rising to 30km^2 every 25 years or so. In October 1980, flooding affected 20km^2 and caused damage valued at 269 million drachmas (1984 value)(Constantinidis, 1984).

Other similar examples are the Karla region in the Thessalia plain (central Greece), the Ioannina plateau in Epirus (north-western Greece) and the Lassithi plateau on Crete. The latter is a flat area of 25km^2 lying at a height of 820m and surrounded by mountains, enclosing a hydrological basin of 130km^2. The place is quite picturesque and has been inhabited since at least the Minoan age. The main stream of the basin traverses the plateau and ends at a group of karstic sinkholes. Owing to their limited capacity, which is only about 12m^3/s, floods occur every year. The floods may cover half the area of the plateau and last from one or two days up to one month (Koutsoyiannis, 1982).

7.4. Floods in the plains

Earlier it was described how floods have been a significant problem since ancient times for the Acheloos and Pinios (Thessalia) plains. Similar problems were met in almost every other plain in Greece traversed by a major river. Since 1900, the flood hazard has been considerably mitigated by the building of major protective works, such as those on the Pinios river (Thessalia plain), on the lower Acheloos river (Agrinio plain), on the Pamissos river plain in Peloponnese, on the Arachthos and Louros rivers (Arta plain) in Epirus, on the rivers Aliakmon, Axios, Loudias and Gallikos (Thessaloniki and Giannitsa plain) in Macedonia, on the Axios river (Artzan-Amatovo marsh), and on the Strymon river (Serres and Drama plain) in Macedonia. It should be emphasised that these measures do not, of course, afford full protection against damage. Usually, they are designed for a return period of between 10 and 100 years, depending on the severity of destruction witnessed on previous occasions; they will function satisfactorily for most floods but do not protect against the rarer, more severe events.

Among such extreme events, the major flood of 24-27 March 1987 on the Thessalia plain may be mentioned, caused by both intense rainfall and snowmelt. The water in the Pinios river rose to over 6.3m in the narrow pass of Amygdalea (normal water level less than 1.0m), 15km above the town of Larissa (with 6401km^2 of basin area upstream) and to 8.0m at the Tempi ravine (normal water level also less than 1.0m), located 18km above the basin outlet (9512km^2 of basin area upstream). The measured discharge exceeded 1000m^3/s at both points. Owing to the narrowness of the channel at these places, significant parts of the Thessalia plain upstream from each were inundated (Fig.9.13).

7.5. The flood risk in urban areas

The continued urbanisation of natural floodplains has created a threat to both the economic utilisation of these areas and human life. In Greece, unfortunately, urbanisation has seldom been combined with the necessary protective infrastructure works such as channel improvements and storm drainage networks. There are, moreover, cases where buildings have been illegally constructed over or very close to ephemeral stream beds. Flooding of urban areas is thus one of the most frequent hazard types in Greece.

This has become a serious problem in Athens, the capital, with its population of about 4 million. Recently (20-22 November 1993), a severe flood in the south-eastern part of Greater Athens resulted in inundation of houses and streets (which turned into streams), carrying off cars and causing other damage to property (Fig.9.14). The storm causing the flood was intense and prolonged but not exceptional. A plot of its severity is shown in Figure 9.15. The data used in this plot were taken from the meteorological station of the National Technical University of Athens, 20km to the north of the flood

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Fig.9.13. (*facing page, upper photo*) The overflow of the Pinios river at Aghia Paraskevi, Tempi ravine, during the flood of 27 March 1987. The actual river bed lies to the left of the photo. (S.Beloukas, Ministry of Agriculture)

Fig.9.14. (*facing page, lower photo*) Cars moved and damaged in a street which was turned into a stream by the flood of 20-22 November 1993, Glyfada, south-east Athens. (Photo from *Eleftherotipia*)

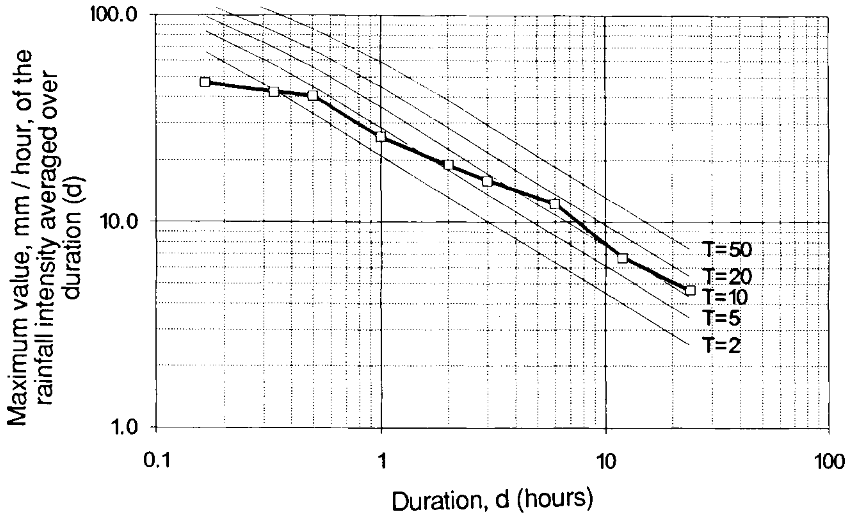

Fig.9.15. Maximum values of rainfall intensity (thick line) averaged over various periods of time for the storm of 20-22 November 1993 in Athens. For comparison, a set of curves (adapted from Memos, 1980) for return periods (T) ranging from 2 to 50 years (thin lines), extracted from historical rainfall data for Athens, is also shown.

centre, but were cross-checked against data from a station near the flood centre. No important differences were found, and it is therefore unlikely that the storm severity was under-estimated. The Figure shows that, for short periods of between 10 and 60 minutes (which are the most critical for floods in urban areas), the storm exhibited intensities corresponding to a return period of less than 5 years, which are normally those with which any typical storm drain system has to cope. However, no such storm drains existed in the flooded areas.

Intense floods also hit the western part of Athens on 6 November 1961 and 2 November 1977. It is estimated that the latter event, in which 36 people lost their lives, had a return period of about 50 years (Xanthopoulos *et al.*, 1977). Interestingly, the storm that caused the flood was probably influenced by the urban heat-island effect, acting on an already unstable air mass (Flokas and Giles, 1979; Liakatas and Nianios, 1980). As a result of the storm, the main river of Attica, the Kifissos, with a drainage basin area of 417km^2, spilled out of its bed on to the adjacent main road, which became a part of the river, causing severe damage and loss of life.

7.6. Dams and reservoirs

Some tens of dams have been built in the last 70 years in Greece, most of them in connection with hydro-electric power generation, others for irrigation or flood prevention and some for water supply. All provide some measure of protection against floods for areas downstream, as they hold back flood peaks. The major dams have been designed for a flood protection level corresponding to either the maximum probable precipitation or a storm with a return period of 10 000 years. In the case of minor dams, the design generally corresponds to a return period of 500-1000 years. Recent research (e.g. Koutsoyiannis, 1994) has provided more reliable methods of estimating storm and flood intensities on which dam design can be based.

The existence of large reservoirs, however, itself creates a potential (though extremely infrequent) risk of severe flooding downstream in the event of dam failure. Considerable research, both theoretical and applied, has been carried out into forecasting such floods (e.g. Xanthopoulos and Koutitas, 1976). Flood propagation resulting from dam failure has been simulated for at least the major dams, in order to estimate the possible hazards, to design warning systems and to plan for evacuation. Two examples may be mentioned: the Mornos and Kerkini dams (Ganoulis and Tolikas, 1981a, 1981b). The Mornos dam, located on the river of that name about 200km west of Athens, is a 126m-high earth-fill dam, 825m in length and impounding a reservoir with a capacity of 780 million m^3. Because the river below the dam is confined in a deep valley, failure of the dam would propagate a mono-dimensional wave, except in the delta area where the flood wave could spread laterally. From simulations, it appears that wave propagation would be very rapid, within a timescale of 25-45 minutes. The risks related to failure of the Mornos dam focus on the villages in the delta area, and on the road along the river valley.

The second example concerns the Kerkini dam, a 15m-high embankment of the natural lake Kerkini on the Strymon river in the Serres plain, Macedonia; it was built for irrigation and flood protection purposes. In this case, wave propagation following dam failure would be two-dimensional and relatively slow (within a timescale of several hours to about a day), owing to the low height of the dam and the broad gently sloping area that lies downstream from the dam.

Attention has also been given to another potential risk, that of a landslide into a reservoir, which might induce a wave overtopping the dam (as in the case of the Vaiont disaster in Italy: see Chapter 12, section 3.3.2). Theoretical research in this field has been carried out by Koutitas (1977) and Gavriilidis *et al.* (1993), and specific reservoirs have been studied.

Fortunately, with one minor exception, no dam failure owing to overflow or to other causes has occurred in Greece. The exception is the case of the small Agras dam which was overtopped during a severe flood. The dam was built in 1951-54 and belongs to a system of hydro-electric works (which includes the two natural lakes of Ostrovo and Nissia). Located about 5km above Edessa in Macedonia, it consists of an earthen embankment 10.5m high with a length of 179m, impounding a reservoir in the Edesseos valley (a tributary of the river Loudias) with a storage capacity of 400 $000m^3$. After a severe rainstorm on 18-19 November 1979, with a 24-hour rainfall depth of 319mm and 421mm at two nearby gauges, the resulting flood was too large to be handled by the regulating reservoir and the dam spillway; the dam was overtopped and seven breaches carved across it (Mimikou, 1993b). A view of the breaches is shown in Figure 9.16. There was damage downstream to property and farmland where the channel levees were unable to control the unregulated discharge. The damage to the dam has since been repaired.

Fig.9.16. A view of the breaches in the Agras dam caused by the flood of 18-19 November 1979

7.7. Flood forecasting systems

Flood forecasting and warning systems are of great importance in the mitigation of the impacts of flood disasters. In Greece, however, the focus of most attention has so far been on the hardware - i.e. protective engineering works - rather than on the software, the means of flood forecasting and decision making. More recently, though, attention has been given to flood forecasting at least for the protection of dams during their construction. For example, forecasting systems have been studied in the cases of the Pournari dam on the Arachthos river (Mimikou *et al.*, 1977) and the Mesohora dam on the Acheloos river (Mimikou *et al.*, 1992) in order to protect them and associated structures such as coffer dams and diversion tunnels during construction. The flood warning systems are based on the monitoring of upstream hydrological variables such as precipitation and water level, and also make use of empirical relationships and nomographs developed for specific locations by analysing historical flood records. Research in this field in Greece is being stepped up, as in many other European countries, and there are at least two European projects concerned with the impacts of storms and floods in which Greek scientists are participating:

1. The project AFORISM (A comprehensive forecasting system for flood risk mitigation and control) aims to study the level of data aggregation and the required interfaces for setting up a comprehensive flood forecasting scheme. In more detail, it is concerned with data acquisition systems, rainfall and rainfall-runoff forecasts (deterministic and stochastic models), flood routing and floodplain models, analysis of flood impacts, decision-making processes, multi-criteria optimisation schemes, and the use of geographical information systems. The Greek contribution focuses on stochastic rainfall and rainfall-runoff forecasts (Xanthopoulos *et al.*, 1993).
2. The project entitled *Storms, floods and radar hydrology* is concerned with the use of weather radar for hydrological purposes such as storm and flash-flood forecasting and warning. The study includes the use of a weather radar system that covers part of central and north-western Greece, including some basins of considerable hydrological interest (Baltas and Mimikou, 1993; Mimikou, 1993a).

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HUNGARY

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1. Introduction

There are two primary groups of geomorphological hazard that affect Hungary, namely, flooding and mass movements. This chapter will deal with each in turn.

2. Areas of potential inundation

Since time immemorial, waterlogged surfaces and river flooding have been particularly important factors in the settlement and lives of the peoples in the Carpathian Basin. Both the Romans and the Magyar conquerors took advantage of marshlands for setting the borders between wilderness and settled areas. A major turning point of Hungarian history is associated with a flood. In 1526, in the crucial battle of Mohács against the Turks, King Louis II drowned in the flooded Csele stream, normally an insignificant tributary of the Danube.

2.1. Geological background

The drainage pattern of Hungary is determined by the country's location in the centre of the Carpathian Basin. The overwhelming majority of river discharge is collected by runoff from the encircling mountain ranges. The central parts of sub-basins within this major depression are characterised by general subsidence continuing through the Quaternary and caused by the tectonic movements of microplates beneath the Great and Little Hungarian Plains. In the Great Hungarian Plain, an approximate balance is struck between the rates of subsidence and fluvial accumulation, which is reflected in the meandering behaviour of the major rivers (Somogyi, 1983), whereas the sediment influx of the Little Hungarian Plain is larger, the braided channel of the Danube reflecting excess of accumulation over subsidence.

Owing to the subduction of the frontal wedge of the microplate beneath the Great Plain, the rate of subsidence varies regionally. A series of marginal depressions has formed and attracts drainage. On the topographic map of Hungary, the 100m contour marks approximately the outlines of abandoned alluvial fans, where recent subsidence rates (now largely due to sediment compaction) are reduced to less than 1mm/year. The area of 26 000km^2 lying below that altitude is potentially liable to flooding.

Not being confined to well-marked valleys, rivers, particularly on the Great Plain, roamed in broad meander belts which were regularly inundated before the regulation works of the last century (Fig.10.1). Along the edges of the alluvial fans on the basin margin, rivers in flood spread out over extensive areas. During floods, considerable accretion took place on the outer flanks of natural levees and, together with artificial dykes, now border the channels of the main rivers (Borsy, 1972). The natural levees were never continuous enough to protect against floods but provided suitable terrain for settlement.

2.2. Characteristics of floods in the Carpathian Basin

Floods in the Carpathian Basin usually result from meteorological events in the surrounding mountains and occur some days later (Jakucs, 1982). There are two times of the year when floods are most likely: one follows early spring snowmelt in the Alps and Carpathians, and the other is generated by early summer frontal rains all over the Danube catchment upstream.

The following types of flood wave occur on the major Hungarian rivers (Csermák, 1987; Kovács, 1979):

a) Individual flood waves emerge after prolonged high-intensity (up to 260mm in 24 hours) rainfall, or after rapid temperature rises causing snowmelt. Both events may occur in almost any part of the basin and its surrounding mountains. Examples are known from the high-gradient Hernád river in northern Hungary (Siku, 1978).

b) When a new flood wave surges over the previous one, even higher flood crests are produced.

c) Flood waves travelling down tributaries may be superimposed upon the floodwave of the main river in a system. A recent flood of this kind led to breaches of the dykes on the Double Körös river in 1980, when record discharges of the tributaries Black and White Körös joined to swell the river to a previously unobserved level (Litauszki, 1980; Szlávik, 1982). The causes may be traced back to the regulation works, as the tributaries are now forced to flow on an active floodplain that is too narrow.

d) Ice-jam floods (Kovács, 1987) are more frequent on the Danube than in the Tisza system, as the Danube lacks any tributary to break the river ice in the 325km-long section between the mouths of the Ipoly and Dráva. A tragic example of ice-jam floods took place in 1838 (Vincze, 1967) when a record water level of 1029cm (as opposed to the 314cm mean water level) was reached. It brought destruction to Pest and Buda, the towns to be united to form the capital city.

e) Floods caused by other forms of damming include the effect of a tributary joining a low-gradient trunk stream. For example, the Körös rivers and the Maros may dam back the Tisza during major floods (Ambrus, 1967; Fig.10.2)

f) Human action, such as breaches of dams, bridge collapses and military acts, have not recently led to major floods. An exception was the 1970 flood on the Szamos, when a breached dyke on the Romanian side of the border allowed water to escape into Hungarian territory, making flood control extremely difficult (Szeifert, 1971; Fig.10.3).

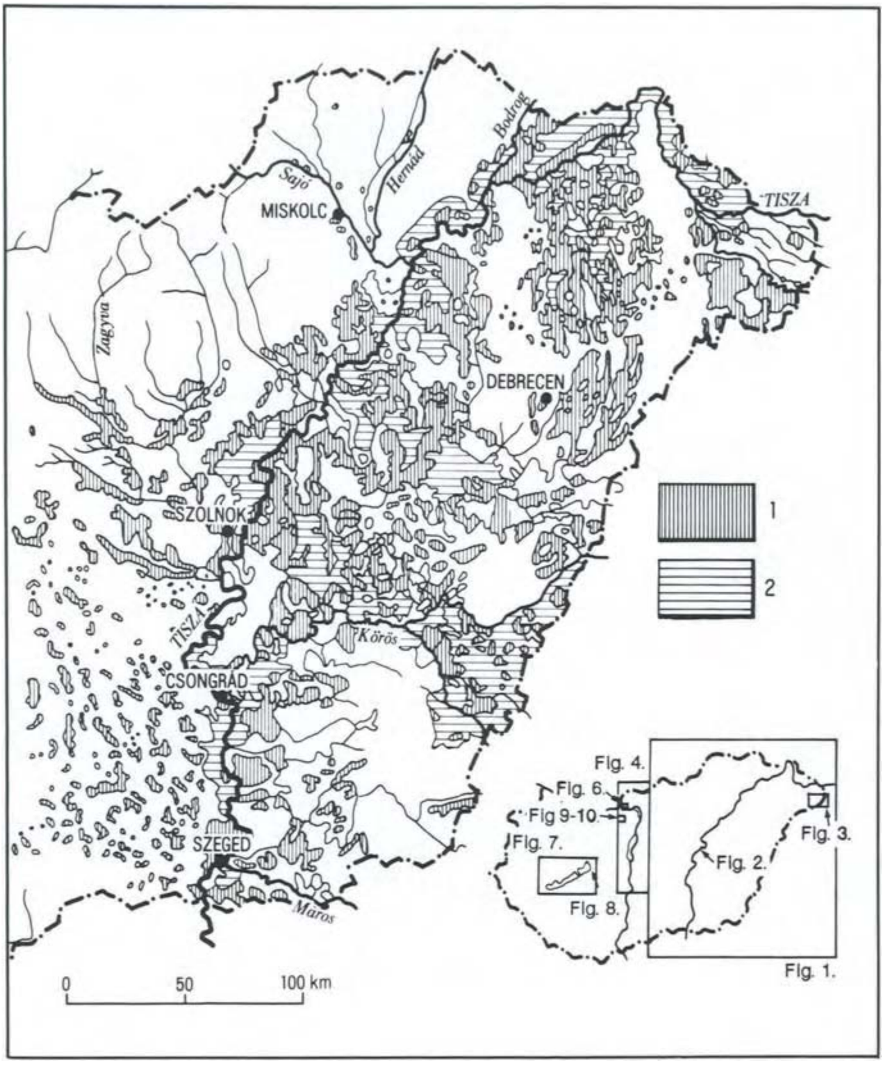


Fig.10.1. Hydrological conditions in the Hungarian Tisza valley before regulation (after the *National Atlas of Hungary*, 1989), with insert showing the areas enlarged in this and subsequent Figures. 1 - areas with prolonged waterlogging for most of the year; 2 - seasonally waterlogged areas (during floods)

Fig.10.2. Bankfull discharge on the Tisza river in May 1970, caused by the damming effect of tributaries (photo: Water Management Documentation Aerial Photography Service)

In 1977 the Research Centre for Water Resources Development (VITUKI) surveyed the area (c. 16 000km^2) endangered by dyke breaches during the 100-year and 1000-year floods (VITUKI, 1981; Fig.10.4). It is fortunate that the main source areas for floods in Hungary are widely separated in terms of location; thus the probability that an emergency will occur simultaneously over the whole of the area theoretically liable to the 100-year flood is very low.

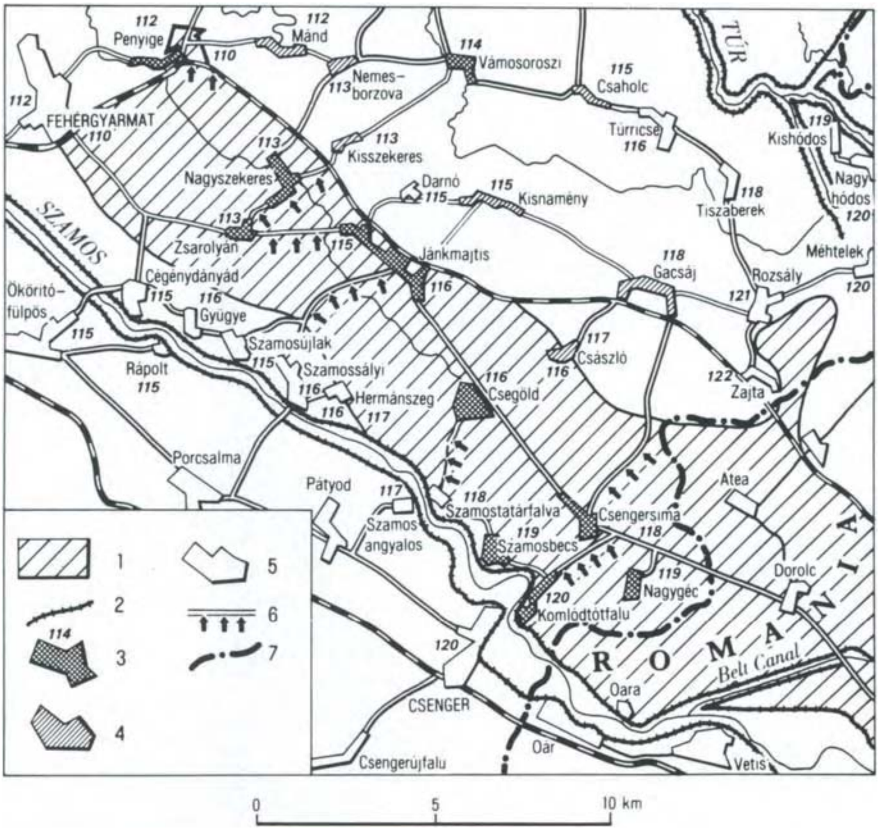


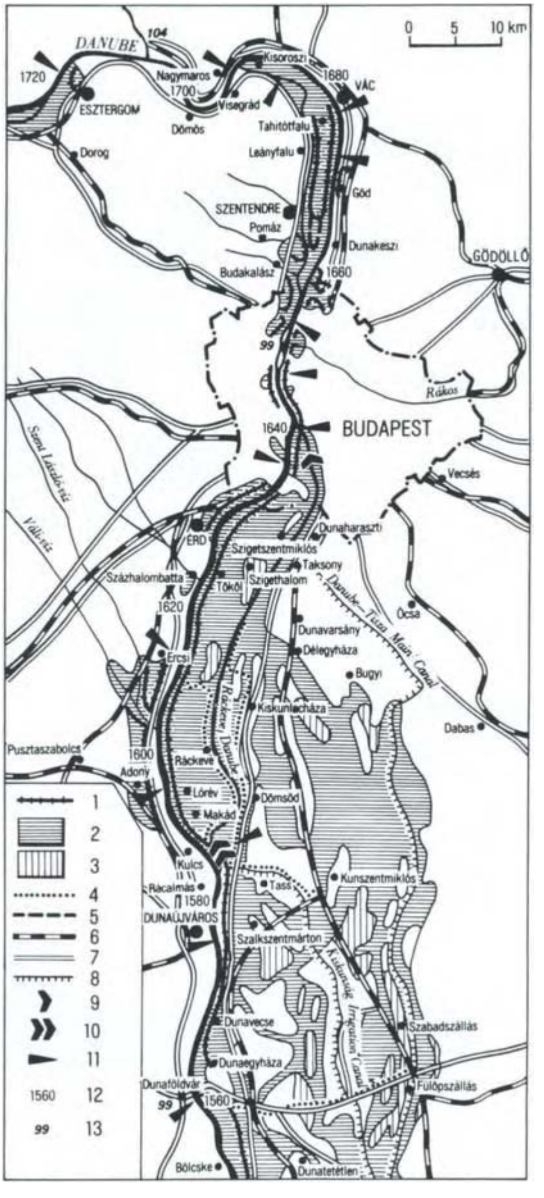
Fig.10.3. The course of the water flooding Hungarian territory along the Szamos river following breaching of a dyke on the Romanian side of the border, 15 May 1970 (Tápay, 1971). 1 - total inundated area; 2 - flood-control dyke; 3 - built-up areas that were inundated, with elevation above sea level (m); 4 - built-up areas that were threatened but saved from flooding; 5 - other built-up areas; 6 - water spills over road embankments; 7. frontier between Hungary and Romania

2.3. Human intervention and river regulation

Deforestation of the upper parts of catchments began to increase runoff as early as the Neolithic period. However, water management as it is conceived today was not needed until the eighteenth century. The sparse population was able to adjust its lifestyles to the presence of water and in this way was relatively immune to the flood hazard (Andrásfalvy, 1973). When Temes county, then in southern Hungary, was

Fig.10.4. Detail from the flood-control map of Hungary (VITUKI, 1981).

1 - main flood-control dyke
2 - boundary of area inundated by the 100-year flood
3 - area affected by the 1000-year flood
4 - major local (subsidiary) dyke
5 - major summer dyke
6 - railway
7 - major road
8 - drainage or irrigation canal
9 - barrage
10 - lock
11 - gauging station
12 - river kilometre mark
13 - elevation of the zero water level of the Danube above sea level (m)



recaptured from the Turks in 1716, farmers settled on the depopulated land. Farming and marketing of farm produce then called for the improvement of water transport and flood control. The 1845 flood on the Tisza river encouraged planning of river regulation works, initiated by the great Hungarian statesman, count István Széchenyi. For the regulation of the Tisza river, two fundamentally opposing concepts were put forward (Lászlóffy, 1982). Pál Vásárhelyi, Hungarian hydro-engineer, proposed numerous meander cut-offs and closely-spaced dykes in order to promote the rapid passage of flood waves, while Pietro Paleocapa, who had directed the regulation of the river Po in Italy, only planned 15 cut-offs and placed dykes farther away from the main channel. For economic reasons, the compromise that was finally implemented did not prove to be the optimal solution. No time was allowed for new channel sections to stabilise themselves, and the replacement of confluences and the regulation of tributaries were neglected until the destructive flood of 1879 at one of the hydrological foci of the basin, Szeged, provided a serious warning that these deficiencies must be dealt with. By the end of the last century the main lines of the flood-control system (1439km in length, of which 119km consist of natural levees and 1320km of artificial dykes; Lászlóffy, 1982) were completed. This achievement is matched in scale only by the Dutch engineering works resulting in the reclamation of the polders.

Although flood waves now pass rapidly enough along the Tisza, river regulation also had adverse effects on the river régime (Zorkóczy, 1987). The active floodplain was reduced to a narrow zone between the dykes, and this is only able to accommodate flood discharges by allowing higher water levels than before. Thus the crests of the dykes have to be raised constantly to cope with flood levels that have risen 2 to 3.5m since regulation. Instead of decreasing, the area theoretically endangered has grown steadily. Higher current velocities of the flooded river result in increased channel incision, so that after regulation, *low* water levels are now definitely lower than under natural conditions (2-2.5m along the middle Tisza). River regulation, however, did not fundamentally alter the prevailing habit of meandering along the Hungarian Tisza section: it only shifted it towards the incising subtype (Somogyi, 1983). This can be proved from the study of cut-offs, which adjusted to the normal sinuous pattern of flow in about 50 years.

2.4. The excess water hazard

River regulation in itself was not able to solve all the water management problems of the Hungarian lowland. Flood-control dykes locally inhibited the drainage of excess water back into the channels (Pálfai, 1988), so that drainage canals, locks and pumping stations had to be built. The total length of canals, which present striking features in the landscape today, now exceeds 27 600km, and their average density for the Tisza lowland is 1.41km per km^2 (Lászlóffy, 1982). However, many parts of the canals are poorly designed and badly maintained: consequently, they often aggravate rather than mitigate the excess water hazard. Even today, recurring damage owing to excess water (even if the term is applied in a narrow sense to mean only surface waterlogging) affects about 1.8 million ha of agricultural land in the Great Plain alone, as well as the outskirts of every third settlement.

A study adopting a physiographic approach to the occurrence of excess water (Baukó *et al.*, 1981) attributed the phenomenon to three groups of factors: hydro-meteorological conditions (cumulative effect of heavy rainfall and low evaporation upon soils of low permeability), the geomorphology of the area (abandoned channels, oxbows and poorly-drained backswamps), and hydro-geological causes (such as the system of groundwater flow).

The danger of excess water accumulation in oxbows is closely related to river regulation. After the rivers were confined within narrow floodplains, the previous channels outside the dykes were left without any sediment supply, and the organic (and some aeolian) matter was insufficient, given the productivity of the forested steppe, to obliterate their scars from the surface. Nor could the deeper oxbows be graded by large-scale techniques of mechanised farming and still collect water from their vicinity. During regulation, some of them were not linked properly with actively-circulating water systems; sometimes, such connections were even blocked by man-made structures, for example, railway or road embankments, which added to the hazard. Potential damage is further increased by the expansion of built-up areas over such tracts of land.

In many instances, the drainage of marshes proved to be ecologically harmful. With the reclamation of the Ecsed marsh (Bodnár, 1987) in the Great Plain, an unparalleled wildlife sanctuary was lost, perhaps the last one of its kind to disappear. The Little Balaton (Baranyai, 1989; Kollár, 1967), south-west of the present Lake Balaton, and the Hanság marshes (Kovács, 1979) in the Little Plain once functioned as filters of nutrients and pollutants, but because of their elimination from the main circulation systems of groundwater and streamflow, the eutrophication of both has now reached a dangerous level.

Drainage measures in the Great Plain also led to adverse consequences for soil quality. The drop in the water table, in an area of semi-arid climate, induced upward movement of capillary moisture, leading to the accumulation of salts in the topsoil. The resulting alkalinisation of low-lying surfaces (former oxbows and backswamps) precludes the use of these areas for anything other than poor pasture, fishponds or rice paddies.

According to the new concept of lowland drainage developed by Kovács (1978) and Pálfai (1985), more attention is to be paid to the requirements of cultivated crops (Járányi and Fekete, 1962), i.e. maintaining a permanent water-table depth of at least 2-2.5m and preventing upward capillary motion in the soil.

2.5. Flood-control systems and geomorphology

The water management policy that was only recently abandoned envisaged dams as the most feasible way to exploit river resources for power, navigation, water supply and so on. Flood control was also seen as a task to be solved by these schemes. On the Tisza, two of the projected dams have been built: the Tiszalök (1954) and the Kisköre dams (1973) with their supplementary works. The Kisköre reservoir has a storage capacity of 300 million m^3 and a maximum water level of 90.5m, while the areas around lie at 87-89m above sea level. The much-debated Bős-Nagymaros Barrage Scheme on the Danube was only partly implemented. This scheme, partly designed to reduce the flood hazard (Góczán and Lóczy, 1990), provoked serious political argument between Hungary and Slovakia. The drop in the water table that would ensue would certainly have an adverse environmental impact in Hungary, varying in intensity according to the pattern of surface relief (Lóczy and Balogh, 1990).

Repeated soil surveys have also indicated that, in the case of the Tisza reservoir, a rising water table (Csipai *et al.*, 1992) in the area 1-2km around it and within 1km of the main irrigation canals leads to intensified meadow soil dynamics (e.g. transformation of chernozems into saline or solonetz meadow chernozems), waterlogging and man-induced (secondary) salinisation (Fekete and Szalai, 1990).

Instead of once-for-all, final solutions, more local schemes and smaller-scale engineering works are now favoured for flood control. In addition to the main dykes, the control system comprises ring dykes (Bencsik, 1971), local dykes (Tápay, 1971) and flood-retention basins. Ring dykes allow more land for settlement and protect it from flooding. Local or subsidiary dykes are built to trap any water released accidentally by dyke breaches. The flood-retention basins have to be planned with regard to the geomorphology of the terrain: use is made of natural depressions suitable for accommodating part of the flood discharge. These are only filled during floods; at other times they are cultivated or forested. In the Körös region, for instance, three major emergency reservoirs were established (Szlávik, 1982): of these, the Mérges reservoir has an area of 1823ha and can hold 87.2 million m^3, and the Kutas reservoir covers 2900ha with a capacity of 36.6 million m^3. Smaller, closed depressions, among others the White Lake of Szeged or the oxbows along the Körös and Hortobágy-Berettyó rivers, also accommodate excess water (12 and 10 million m^3 respectively).

Over the extensive floodplains of Hungary, waterlogged areas represent a local but frequently recurring and widespread hazard for agriculture and other land uses, posing an even greater threat than the flood hazard. Pálfai (1988) claims that, although areas with no excess water are usually not prone to flooding, there are some marginal alluvial fans that are unaffected by inundation but do experience occasional high water-table conditions, and in these cases excess water may cause damage.

3. Mass movements

In Hungary, mass movements are rather localised phenomena, and certainly so compared with the flood hazard. Rapid movements are mostly associated with hilly and upland regions built of unconsolidated deposits, having relatively high relief and numerous valleys dissecting the surface. Most of these areas are densely populated, and to avoid the threat of serious damage, a detailed knowledge of the spatial distribution of this hazard is important.

For this reason, a project to map and evaluate mass movements in Hungary was launched in 1971-72. It aimed to provide comprehensive information on mass movements for practical purposes, investigating cause-and-effect relationships and the significance of natural and human factors in the triggering of these processes. The processes and landforms of unstable areas were classified, and individual and multiple types of movement were identified (Pécsi and Juhász, 1974).

Fig.10.5. Main types of mass movement in Hungary (Pécsi and Juhász, 1974)

1 - rockfall
2 - earth or loess fall
3 - planar slide
4 - rotational slide
5 - rotational slump
6 - combined slide and mudflow
7 - earthflow
8 - rock slide, talus
9 - creep on grass slope
10 - karstic collapse
11 - piping
12 - collapse caused by human activity

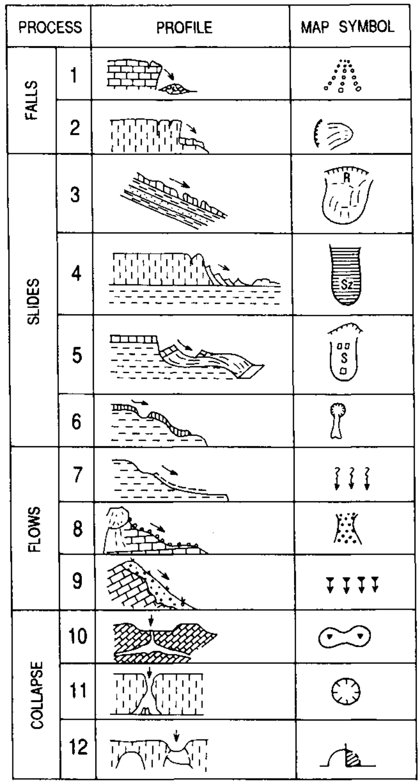


Fig.10.6. (*facing page*) Detail from the engineering geomorphological map of Esztergom and surroundings (Juhász, 1972; original scale 1:10 000)

I *Relict mass movements*: 1 - hummocky terrain of stabilised palaeo-slides; 2 - slopes with palaeoslides

II *Active mass movements*: 3 - landslide scar; 4 - depressions between landslide lobes; 5 - temporarily inactive slopes; 6 - slopes with potential landslide hazard; 7 - slopes with active landslides

III *Forms of fluvial erosion and deposition*: 8 - slopes with rills; 9 - slopes subject to sheet-wash; 10 - gully; 11 - gorge; 12 - alluvial fan; 13-16 - Danube terraces; 17 - stable low river-bank

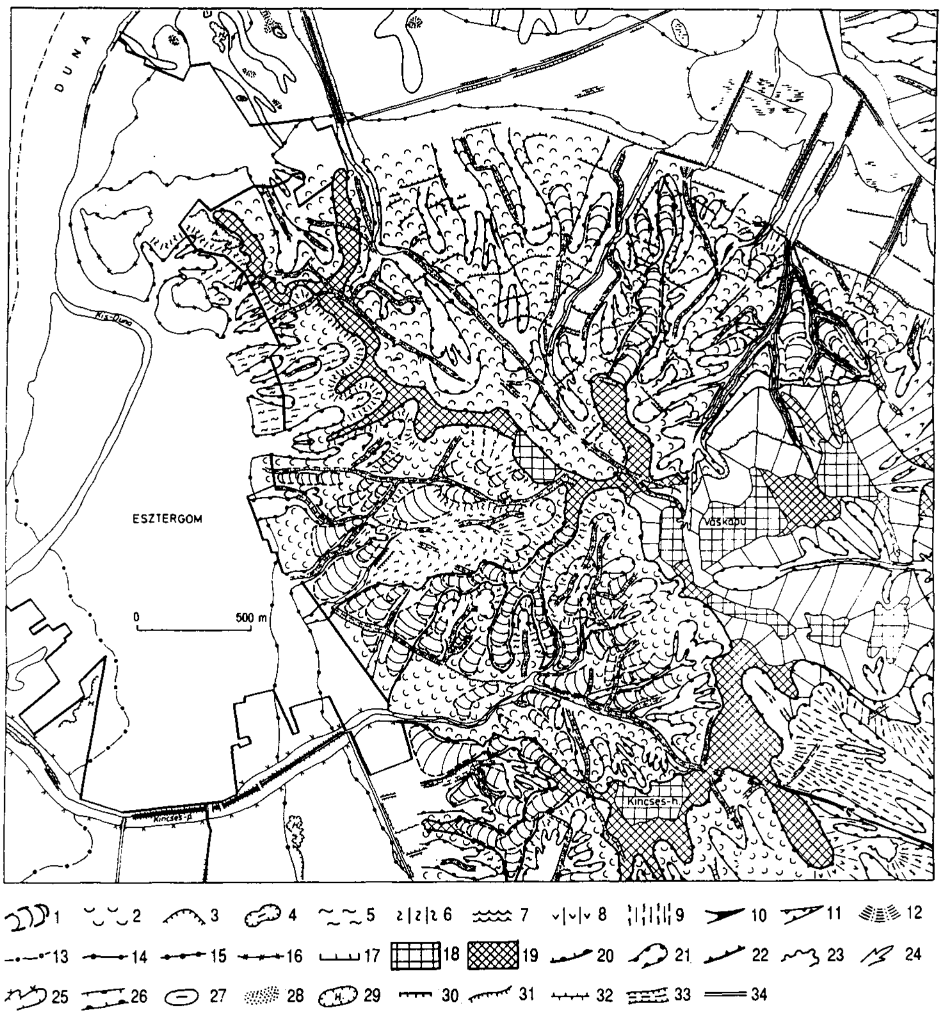
IV *Other forms*: 18 - plateau; 19 - ridge; 20 - dry valley remodelled by fluvial erosion; 21 - dry valley; 22 - horst; 23 - scarp; 24 - valley with floodplain; 25 - margin of valley floor; 26 - other valley; 27 - blow-out; 28 - sand dunes

V *Man-made forms*: 29 - opencast mine; 30 - man-made terrace; 31 - road or railway cutting; 32 - dam; 33 - sunken road in loess; 34 - road

3.1. Mapping of mass movements

The inventory of landslides compiled for the Hungarian Geological Survey includes data on the location, the geological, hydrological and geomorphological conditions, and the principal soil mechanics parameters. For the inventory of all areas of possible movements, geomorphological maps on the scales of 1:500 000, 1:25 000, 1:10 000 and, for some representative areas, 1:4000 were compiled. These maps show the most frequent types of mass movement in Hungary (Fig.10.5).

On the more detailed maps (Fig.10.6), smaller-scale landforms and landslide ele-



ments, such as slumps or failure surfaces, are also depicted. Where it was considered necessary, certain geomorphological parameters such as slope categories were also shown.

3.2. Review of landslides in Hungary

Against the background of tectonics, stratigraphy and geological evolution, the following major regions of mass movement hazard may be identified:

(a) In the *Transdanubian Hills*, landslides are mostly associated with the Mio-Pliocene clays of the Pannonian formations, and with some Pleistocene palaeosols with high clay content and potential slip surfaces. In the western borderland of Hungary (the Vend country), movements occur primarily in Pleistocene loam and extend below the surface to depths of only 1-3m, or locally down to the Pannonian clay. The combination of sediment types, structure, humid climate and steep slopes is particularly favourable to slumping. Slumps are most frequent on the gentler sides of asymmetrical valleys (e.g. the Kapos and Zala valleys: Ádám, 1957; Juhász, 1972; Miholics, 1968; Szilárd, 1967).

(b) Mass movements have also been important in the evolution of the intramontane basins and marginal hills of the *Transdanubian Uplands*. The differences from region (a) are first of all due to differences of relative relief and sediments. Foreland pediments on unconsolidated sediments are extensive and poorly dissected (e.g. the Bakonyalja and Vértesalja Hills). In present geomorphological conditions, the sands and gravels derived from erosion of the mountains are not liable to mass movements. Only the tracts of the former Upper Pliocene pediment with its greater altitude and stronger relative relief (such as the margins of the Gerecse Mountains at Esztergom (Fig.10.6) and of the Bakony mountains at Ajka and Dorog, where it is intensely dissected) show landslide phenomena. The sediments primarily involved in rotational slides are Oligo-Miocene clays, sands and marls, with mantles of Pleistocene deposits of varying thickness. Translational slides have transported large blocks of basalt in the hills bordering Lake Balaton on the north - Badacsony, Szentgyörgy-hegy, etc. (Borsy *et al.*, 1987).

(c) Active slumping characterises the bluffs of the *Danube terraces*. Depending on lithology and the geomorphological situation, unstable areas along the Danube can be grouped as follows:

- Pleistocene gravels of the Danube terraces on the margins of the Gerecse, Pilis and Buda mountains overlie Tertiary clays, sands, marls and gravels, and locally also Mesozoic limestones. The terraces are frequently mantled by various types of loess (with intercalated palaeosols, attaining thicknesses of 20m) and travertine. Slumping affects the loess mantle where it has been dissected by streams cutting down into the Pannonian clay. Argillaceous palaeosol horizons and marine clays function as slip planes (Ádám and Schweitzer, 1972; Pécsi, 1955).
- The various types of mass movement (slumps, planar and rotational slides) are well represented around Esztergom, at the western entrance to the Danube Bend, where the surface is underlain by unconsolidated Oligocene clays and sands, and Miocene andesite. The present landscape is largely the product of Late Pleistocene and Early Holocene slumping and sliding (Juhász, 1972; Fig.10.6).

A particular combination of lithological, hydrogeological, hydrological and geomorphological factors is responsible for the landslides along the bluffs of the middle Danube. The loess sequence with Pliocene sands and clays at its base and intercalated palaeosol horizons forms a plateau whose eastern margin is undercut by the river. The resulting steep bluffs are affected by lateral erosion and slide lobes are regularly removed. Rotational slides and bank falls are characteristic and have been studied by Domján (1952), Egri and Párdányi (1968), Juhász and Schweitzer (1989), Karácsonyi and Scheuer (1972), Lóczy, Balogh and Ringer (1989), Pécsi (1971a, 1971b), and Pécsi, Juhász and Schweitzer (1976).

- Another bluff rises to a height of 20-40m to the east of Lake Balaton, containing Pannonian clays and sands with a loess mantle. It is highly unstable and repeated movements take place (Figs.10.7-10.8). The hazard here is serious since the shore of Lake Balaton is the foremost recreational area in Hungary, densely built-up, and the mapping and monitoring of movements is therefore vitally important (Juhász, 1978). The damage caused by frequently recurring slides has necessitated the relocation of the railway into the lake itself, where it is built on piles.

(d) Mass movements are responsible for various features in the hilly areas of the intermontane basins and foreland regions of the *North Hungarian Uplands*. A mosaic of dismembered and tilted blocks of Oligo-Miocene clays and sands, with varied stratification, intense dissection and strong relief all favour landsliding. In the basins,

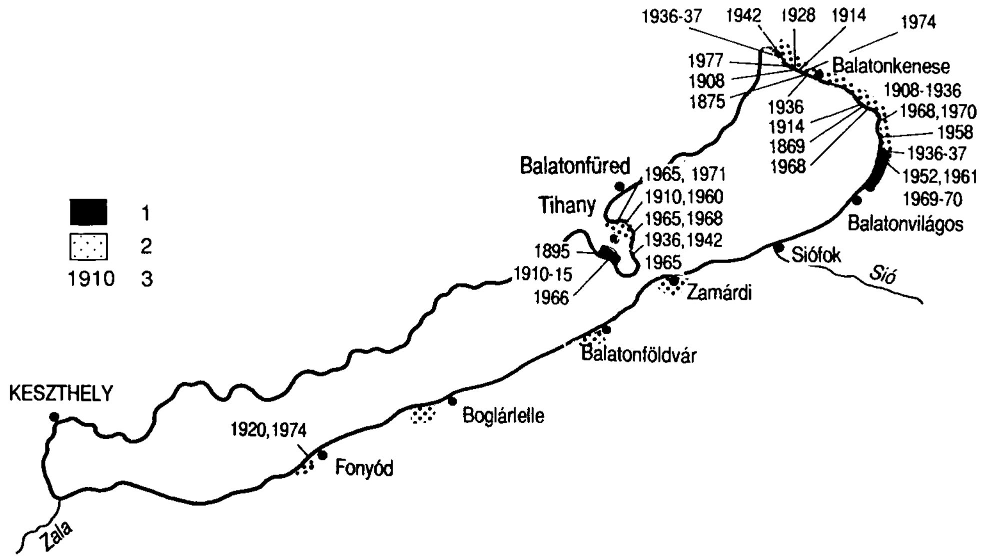


Fig.10.7. Dates of major mass movements of the Lake Balaton bluffs (Fodor and Kleb, 1986). 1 - Lake Balaton bluffs; 2 - bluffs behind the shoreline; 3 - year of movement

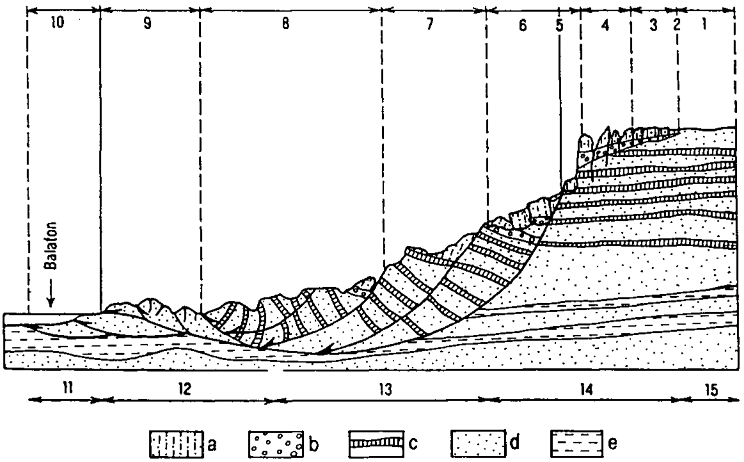


Fig.10.8. Section through the Lake Balaton bluff at Balatonkenese (Juhász, 1978).
1 - zone potentially at risk from movement; 2 - beginning of cracks; 3 - crack zone; 4 - earth pillars, liable to collapse; 5 - landslide scar; 6 - zone of fallen blocks; 7 - zone of rotational landslide hazard; 8 - temporarily stable slope; 9 - upthrust toes of rotated landslide masses; 10 - remnants of old stabilised slides; 11 - stable basal zone; 12 - zone of compressive stresses; 13 - transitional stress zone; 14 - zone of tensile shear stress; 15 - zone at present free from shear stress. a - sandy Pleistocene loess; b - Pleistocene fluvial gravel; c - Pannonian (upper Tertiary) variegated clay; d - Pannonian sand; e - Pannonian grey clay

landslides are associated with tectonically pre-formed valley systems, and relict slide lobes provide source areas for younger slumps and slides. The smaller slumps start at slope inflections and even today they are important factors in the valley evolution (Hevesi, Juhász and Balogh, 1978; Peja, 1956).

A particularly disastrous event took place near the village of Arló in the Szuhony valley. A valley side 140m in height, built of Miocene clay marls collapsed, producing landslide lobes that piled up to form a barrier in the valley, and impounding a lake 300 x 400m (Juhász, Peja and Leél-Őssy, 1974).

The major slumps as well as planar slides and slow creep processes on the Sajó-Hernád interfluve have been studied in detail by Szabó (1985), with particular emphasis on the types of slip plane.

3.3. Movements induced by human activities

A special problem is presented by the subsidence that occurs in areas of deep mining. Around Dorog (Figs.10.9 and 10.10), Komló, Salgótarján, Sárisáp, Oroszlány, Dudar,

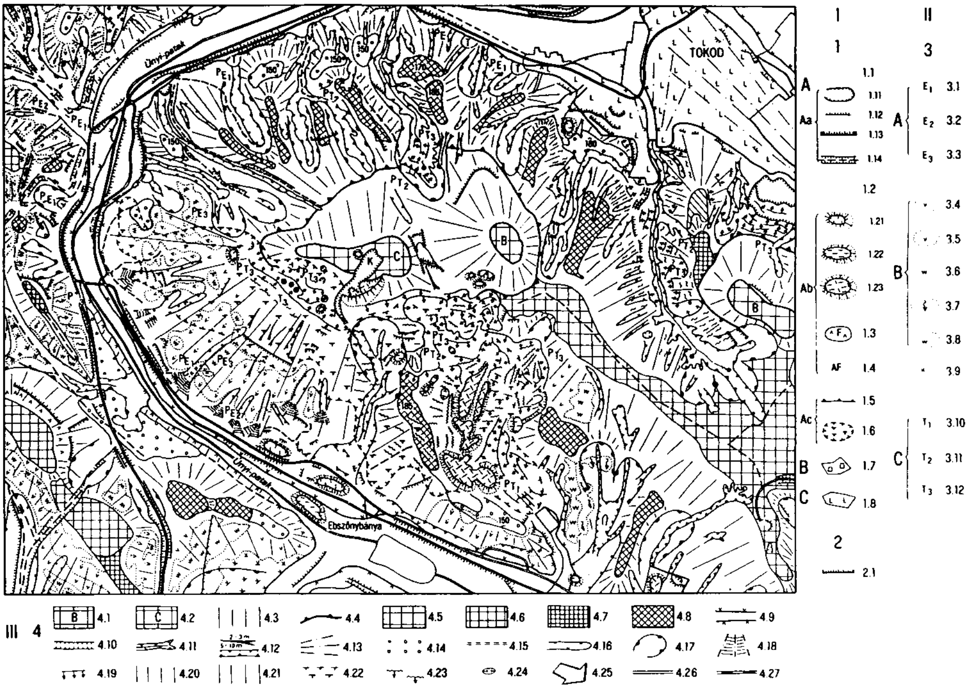


Fig.10.9. The effects of human activity on the land surface around Dorog (Juhász, 1974)

I: *Resulting from human activity*:

Aa - extraction of material (1.11 - stone quarry, 1.12 - road/railway cutting, 1.13 - man-made slope, 1.14 - sunken road); Ab - accumulation of material (1.21 - active stable waste heap, 1.22 - active unstable waste heap, 1.23 - inactive stable waste heap, 1.3 - landfill, 1.4 - potential landfill site); Ac - geotechnical activity (1.5 - man-made scarp, 1.6 - collapse caused by deep mining); B (1.7) - area developed for industry, housing etc.; C (1.8) - partly developed area; D - effects of cultivation (2.1 - terracettes)

II: *Resulting from natural processes*:

A - rates of erosion (E_1 - decelerating, E_2 - constant, E_3 - accelerating); B - surface processes (3.4 - areas of sheet-wash, 3.5 - areas stripped of soil, 3.6 - areas of deposition, 3.7 - area with rills, 3.8 - area with gullies); C - rates of sliding (T_1 - decelerating, T_2 - constant, T_3 - accelerating)

III: *Relief types*:

4.1 - horst; 4.2 - low horst; 4.3 - structural slope; 4.4 - horst margin; 4.5 - plateau; 4.6 - broad ridge; 4.7 - interfluve; 4.8 - narrow ridge; 4.9 - stream valley; 4.10 - gorge; 4.11 - valley head; 4.12 - gully; 4.13 - alluvial fan; 4.14 - terrace; 4.15 - abandoned stream channel; 4.16 - dry valley; 4.17 - pseudocirque in loess; 4.18 - scree; 4.19 - landslide (*continued on next page*)

scar; 4.20 - unstable slope; 4.21 - stable slope; 4.22 - area liable to sub-surface collapse; 4.23 - collapse, crack; 4.24 - undrained area; 4.25 - built-up area; 4.26 - road; 4.27 - railway

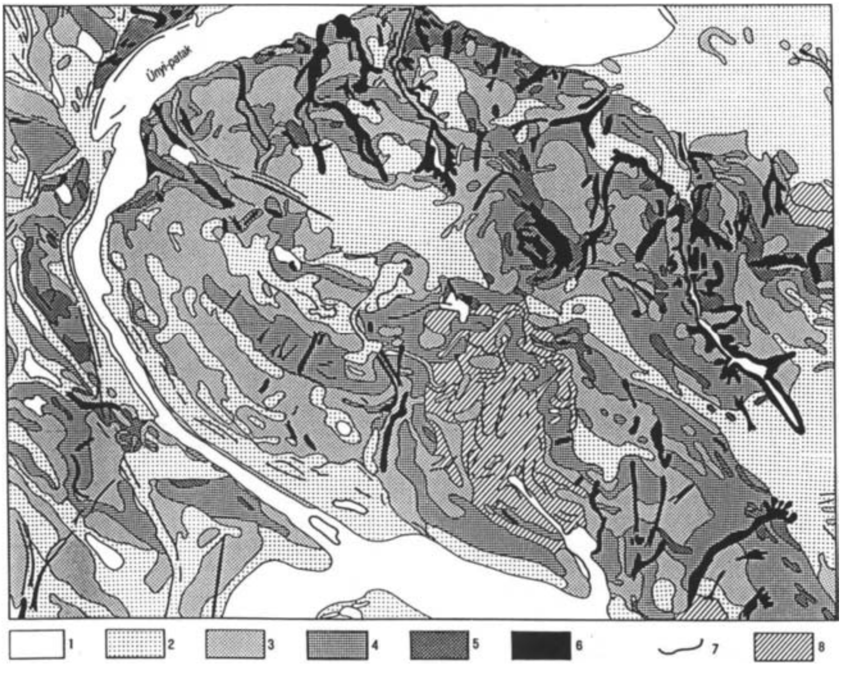


Fig.10.10. Slope map of the area around Dorog (Juhász, 1974). 1 - less than 2°; 2 - 2-5°; 3 - 5-10°; 4 - 10-20°; 5 - 20-30°; 6 - over 30°; 7 - scarp; 8 - built-up area

Ajka, Tatabánya and other coal-mining districts, collapses of 10-50m in diameter are increasingly frequent, and have rendered thousands of hectares of land useless.

A different problem, but one also giving rise to subsidence, is linked to the extensive cellar systems built over hundreds of years beneath some towns, such as Eger, Szekszárd, Pécs and Budapest. The precise locations of these cellars were not recorded and this increases the risk of collapse and surface subsidence. During detailed geomorphological mapping in some areas, these cellar systems were also surveyed and mapped (Hevesi, Juhász and Balogh, 1978; Juhász and Schweitzer, 1989). Such mapping is essential before any development can safely take place in areas threatened by subsidence. There are instances where this warning has not heeded, as in the cases of Komló and Dunaújváros, and it must always be remembered that subsurface instability can seriously endanger engineering construction.

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IRELAND

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1. Introduction

Ireland lies on the western edge of the European continental shelf and possesses a considerable variety of geological and geomorphological features, many of which provide the conditions for a wide range of natural hazards. The discontinuous rim of deeply dissected mountains and plateaus contains extensive stretches of unstable slopes where landslips, debris flows and rockfalls are frequent. The core of the island is the low-lying Central Lowland which is mainly floored by Carboniferous Limestone where solution features are widespread; especially in the Burren Plateau and the Gort Lowland of County (Co.) Clare (Fig.11.3), the limestones display a variety of impressive karstic landscapes.

Virtually the whole island exhibits the strong imprint of successive Quaternary glaciations, with over-steepened slopes in the mountains and copious quantities of glacial drift (deposits) and soliflucted debris at all levels. These relatively "soft" materials form considerable segments of the Irish Sea coastline where erosion of the drift cliffs is a serious problem. Glacio-isostatic recovery may now have either ceased in the northern half of the island, or is proceeding at a very low rate (perhaps 0.1-0.5 mm/year). Any such movement is likely to be outweighed by present-day sea-level rise (about 1-2 mm/year) which affects the whole island and which may be responsible for the accelerated erosion of drift cliffs and coastal dunes, as well as the landward migration and erosion of coastal barrier beaches in Co. Wexford (Orford and Carter, 1982; for a map of the counties of Ireland, see Fig.11.3C). Future global sea-level rise could constitute a serious problem for some low-lying coastal cities, such as Cork and Belfast.

Tectonically, the island is a relatively stable area, experiencing few significant earth tremors, and mercifully the island's surface has been dented by only a very few and small meteorite fragments in the last 100 years!

The climate is equable though damp; in the Central Lowlands, the extensive rainfall and the low relief have not only encouraged the growth of large raised peat bogs but also provided ideal conditions for occasional extensive flooding. In parts of the uplands where slopes are less than 15°, the climate allows extensive blanket peats to develop.

Winds of moderate to severe intensity are experienced from time to time, especially along the Atlantic seaboard and, to a lesser extent, on Irish Sea coasts (Cruickshank *et* *al.*, 1962). The strength of the winds promotes wave erosion and can cause dune instability; and as they are associated with deep low-pressure systems, they are also responsible for bringing exceptionally heavy rainfall to wide areas (Betts, 1990b, 1991; Orme, 1970).

2. Flooding and the flood hazard

About three-quarters of Ireland lies below 150m. Large areas are susceptible to flooding in spite of extensive land drainage schemes which began in the period 1843-50 (Kilroe, 1907) and which have continued to the present century. The area of the Shannon catchment is equivalent to about one-fifth of Ireland, and the river Shannon (280km long) drains much of the Central Lowlands. Its gradient is very gentle - only 15.5m in the 220km (about 1:14 000) between Lough Allen (*lough* = lake or coastal inlet) and Lough Derg - though from Lough Derg to Limerick it steepens to 30m in 30km (1:1000). Nearly all the main tributaries are also gently graded, and consequently there are broad areas that are liable to experience flooding, especially north of Lough Derg in the marshy areas (*callows*) beside the Shannon.

It is the frequency and persistence of rainfall, combined with high relative humidity and limited evaporation, rather than volume of rainfall which is important. Average annual rainfall in the Central Lowlands varies between 700 and 1200mm: on the mountains and plateau rim it rises to about 3000mm, the higher values being recorded on the western seaboard. Rainfall variability is low (6-12 per cent) and the number of rain days is very high, from $\leq$200 in the south-east to $\geq$250 in the west and north-west. Given these conditions of rainfall and low river gradient, it is not surprising that extensive waterlogging occurs and that wide areas of peat bog and gleyed soils have developed. After heavy rainfall or rapid snowmelt, longer-term inundations and even flash floods may take place (Orme, 1970).

In 1970 there were still 20.25km^2 subject to flooding between Lough Allen and Lanesborough, 9.5km^2 between Lanesborough and Athlone, 37.7km^2 between Athlone and Meelick and 11.2km^2 downstream from Meelick. Subsequent remedial measures have undoubtedly reduced these figures somewhat, but the flood hazard remains a serious problem. The prediction that few of the original raised peat bogs of central Ireland (Fig.11.8) will remain after 1995-2000 because of commercial exploitation may well point to further drainage problems.

Although thunderstorms are relatively rare in Ireland, averaging only 4-7 days per year, their effects can be catastrophic. Severe thunderstorms on 27-29 June 1986 over the Yellow River catchment in Co.Leitrim resulted in a series of high-magnitude flood events and peat-bog failures (Coxon, Coxon and Thorn, 1989). Most of the rain generated by the storms fell in 3 hours, though there was some rainfall over 6.5 hours. A total of 110mm was recorded with an estimated peak intensity of 31mm per hour. Coxon, Coxon and Thorn (1989) showed that the return period for such an event is at least $\geq$50 years; more likely, it is 200-500 years or even 400-2500 years, depending on the method of calculation. The overall effects of the flood included severe bank erosion, gravel bar formation and migration together with chute formation along the channel, some landsliding and no less than 13 peat-bog flows involving 35 000m^3 of material.

Betts (1992) has reported that flood events have become more frequent in the Glens of Antrim and also in the Tow valley inland from Ballycastle (Fig.11.1). Afforestation on the Antrim Plateau might have been expected to decrease the frequency of flash floods but drainage of the blanket peats prior to tree planting has had the opposite effect which may continue even 20 years after initial planting.

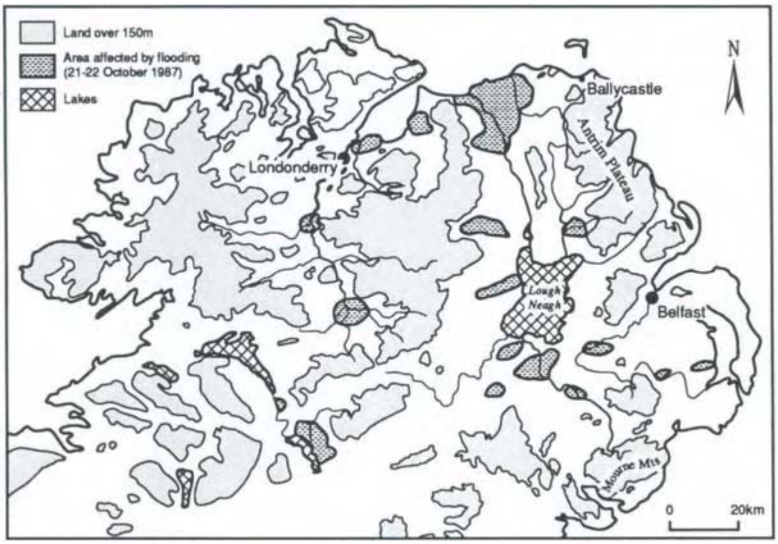


Fig.11.1. Flooding in Northern Ireland, 21-22 October 1987 (after Betts, 1990)

Figure 11.1 shows the extent of flooding in northern Ireland on 21-22 October 1987 (Betts, 1990a). Most of the uplands received over 75mm during this event, rising to 137mm at one gauge in Co. Armagh. Intensities ranged up to 10 mm/hour; return periods were estimated at 160-250 years. There was widespread flooding of both farmland and urban areas; antecedent rainfall had lowered the infiltration capacity, and the low gradients of river channels combined with inadequate channel dredging and bank protection presented further problems. Other comparable events in Northern Ireland in recent years have been those of 1 August 1980 (97mm of rain in 45 minutes on Orra Beg), 27-28 October 1990 (Betts, 1992) and 20-21 December 1991, all in north Antrim.

There is also a flood hazard for coastal cities close to sea level such as Belfast and

Cork. Belfast experienced over 200 flood events between 1902 and 1977 resulting mainly from heavy rainfall but also from a coincidence of such rainfall with high spring tides (Prior and Betts, 1974). In Cork, 292 flood events were recorded between 1841 and 1988 (Fig.11.2), all related to rainfall and tidal conditions (Tyrrell and Hickey, 1991). Storm surges associated with easterly or south-easterly winds have been accentuated by the shape of Cork harbour and estuary: as many as 137 floods between 1937 and 1988 may be attributed to this factor alone. Also noteworthy is the increase in the number of floods this century, as has been the experience of many other coastal sites in the British Isles. The effect of current world sea-level rise must be a factor demanding careful evaluation in all cases.

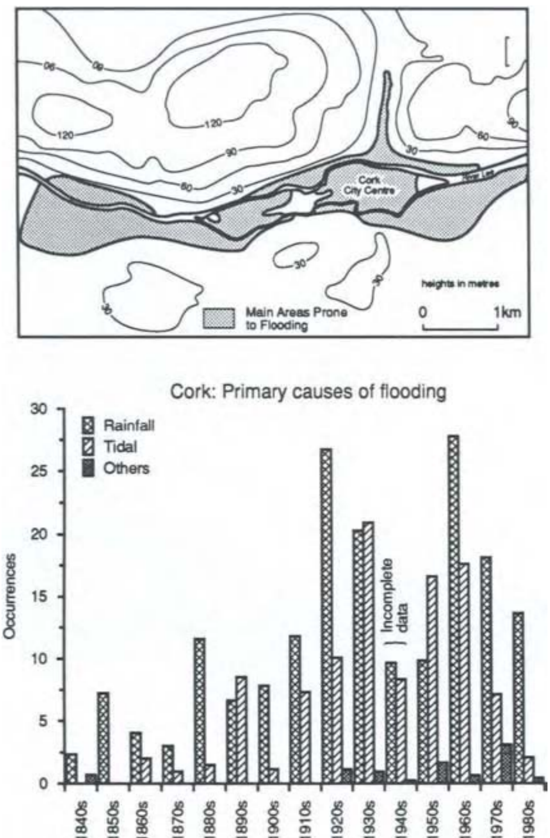


Fig.11.2. Flood events in Cork City, from the 1840s to the 1980s (after Tyrrell and Hickey, 1991)

3. Karst-related hazards

The lake-studded Central Lowland (Fig.11.3A) coincides broadly with the outcrop of the Carboniferous Limestone except in the north-east, north of the River Boyne. Sandstones and shales within the Lower Carboniferous mean that the extent of the true limestone is considerably less than indicated on the map.

Much of the limestone is also obscured by thick deposits of glacial drift although this thins west of the Shannon. Many solution features are undoubtedly concealed by the drift and raised peat bogs, for example in Co. Meath, Westmeath and Offaly, where

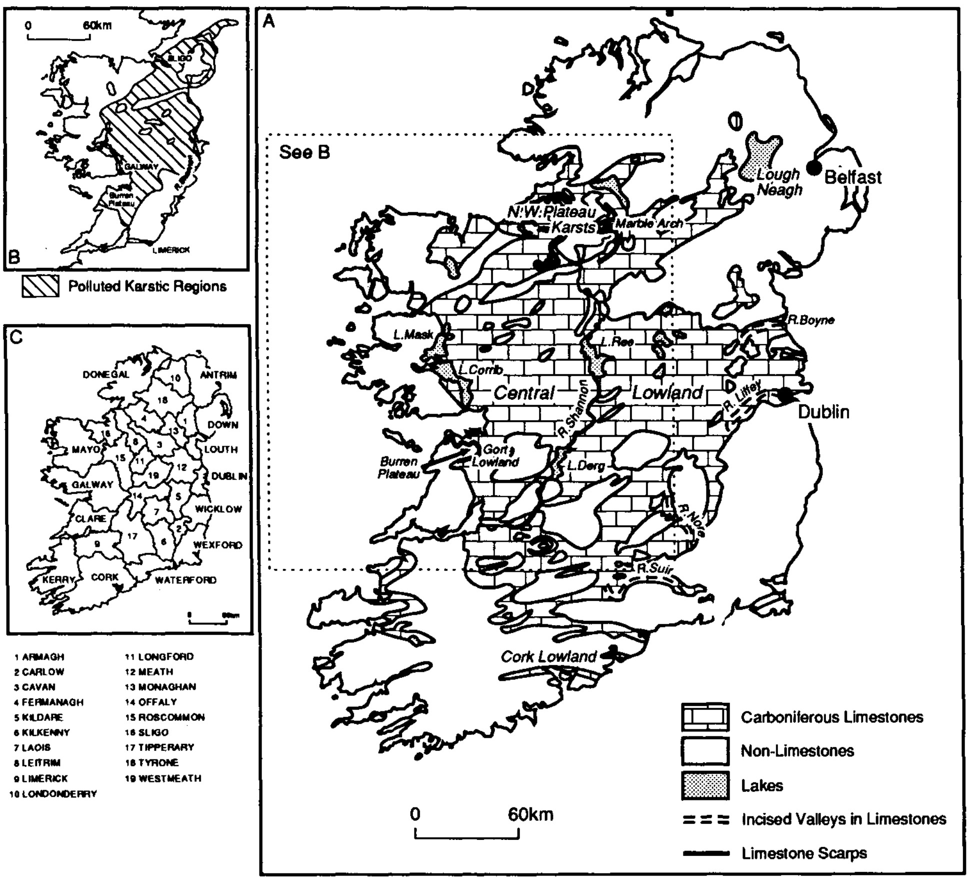


Fig.11.3. A. Main areas of limestone and some karst features in Ireland. B. Karst regions most susceptible to pollution (after Aldwell *et al.*, 1988). C. Map of the counties

geophysical surveys suggest the presence of large water or debris-filled subterranean caverns over a total distance of 115km. Some of the many lakes may occupy ice-scoured hollows in the bedrock where drift provides an impervious base.

Cave systems are widespread, and in the Cong region between Loughs Mask and Corrib, in the Gort Lowland, on the Burren Plateau and the Marble Arch Upland, karst features appear. The poorly organised groundwater system indicates recent karst development and active solution processes, with the potential for cavern collapse (Williams, 1970). The Gort Lowland and, to a less extent, the Burren display excellent examples of ephemeral lakes called *Turloughs*, also seen along the shores of Galway Bay. The turloughs can hold water during winter months when heavy rain causes local back-up of water in subterranean conduits, leading to flooding of valuable farmland.

Although there is no catastrophic subsidence, mainly because of the strength of the Carboniferous Limestone, periodic flooding of some depressions, the presence of extensive cave systems and fluctuating water tables, cause serious problems for water supply and waste disposal over wide areas, especially west of the River Shannon (Aldwell *et al.*, 1988; Fig.11.3B). In the karst areas of western Ireland, there is not only a lack of surface water but a high proportion of failed wells, owing to the localisation of water flow in discrete conduits, tunnels and caves. The groundwater may also be vulnerable to pollution for several reasons. There is inadequate mechanical filtration in areas where the drift cover is thin or absent; the surface water then runs freely into the underground system, sometimes flowing at rates of hundreds of metres per hour, so that chemical reactions have insufficient time to reduce pollution levels. Scarcity of clay minerals limits the ability of pure limestone to absorb potassium, a major product of the breakdown of organic wastes from farming. The use of swallow holes or old quarries as landfill sites for domestic refuse also creates problems because of the speed of possible transfers of pollutants to household water supplies. Groundwater quality can thus alter significantly and rapidly, especially after periods of heavy rainfall. Rigorous groundwater sampling is therefore essential in areas such as the western limestone districts dependent on this source for water supply (Coxon, Coxon and Thorn, 1989; Thorn and Coxon, 1989).

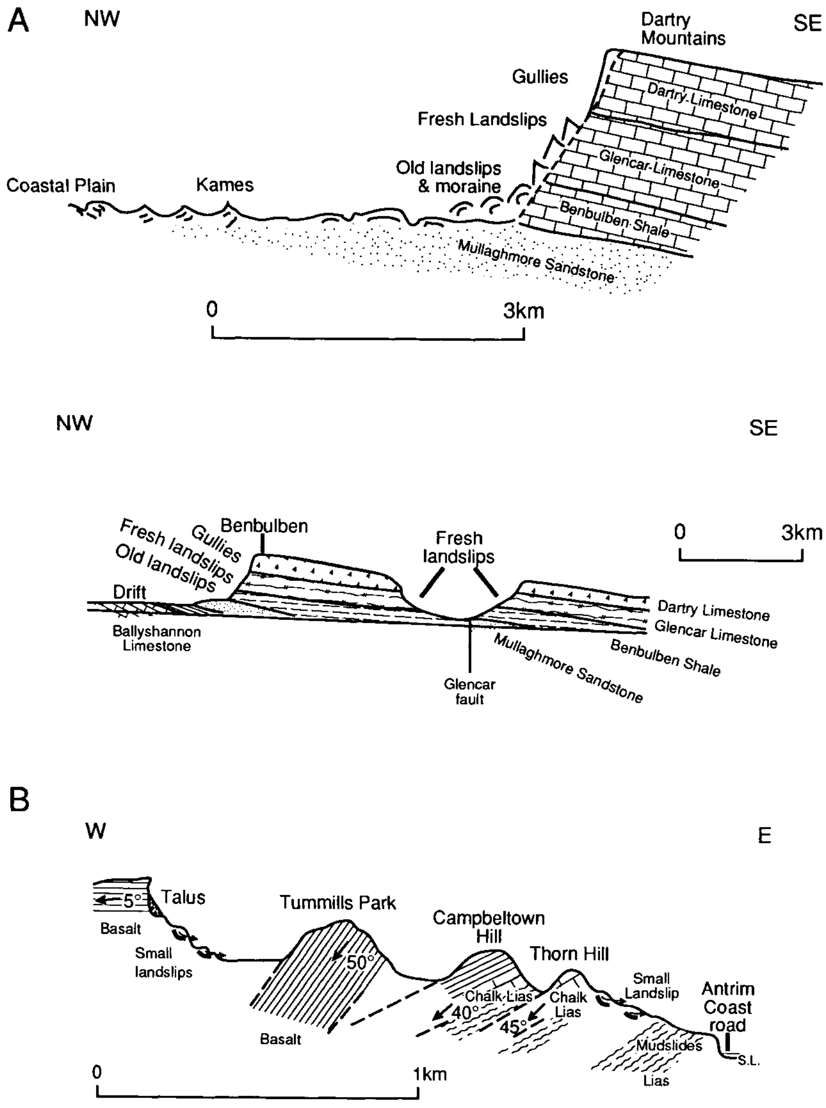
4. Mass Movements

4.1. Rotational slides

Prominent escarpments form the western edge of a block of Carboniferous sediments (Fig.11.4A), including limestones, shales and sandstones, above the drift-clad coastal

Fig.11.4. (*facing page*) A. Landslip sites in the Dartry Mountains, Glencar, and on Benbulben, Co.Sligo (diagrammatic geological cross-sections after Oswald, 1955). B. Multiple rotational landslips between Black Hill and the Antrim coast road, 12km north of Larne, Co.Antrim (composite profile after Davies and Stephens, 1978).

lowlands of Co. Leitrim and Sligo (Oswald, 1955). The Dartry Limestone is massive and well-jointed, producing sheer cliffs below the westward-facing plateau edge and above Glencar. The Glencar Limestone maintains very steep slopes but has many shale partings which generate springs lying at the head of a series of deeply incised gullies. The impermeable Benbulben Shale outcrops at the base of the escarpment above the strong Mullaghmore Sandstone. The junction of the shales with the overlying limestones



provides an important slip plane for a series of rotational landslips on the north-west flank of the Dartry Mountains, below Benbulben and on the northern side of Glencar. A series of old landslips is overlain by glacial drift, but the young landslips and related gullies dissecting the escarpment are currently active.

Similar rotational slides occur in the Magho area, south-west of Lough Erne. These now appear to be stable but provide steep surfaces on which shallower rotational slides and debris flows in the Calp shales continue to create problems above the main Enniskillen to Belleek road. The weathered shales contain a high proportion of illite, have a moderate to high plasticity and absorb water readily, so that conditions favour reduction in shear strength and slope instability (Prior and Graham, 1974).

Large rotational slides, apparently now stable, are characteristic of the eastern edge of the Antrim Plateau and the corresponding western edge overlooking Lough Foyle and the Roe valley (Stephens, 1970). In both areas a thick pile of basaltic lavas overlies a sequence of Cretaceous chalk, Liassic (lower Jurassic) shales and Triassic sandstones, though the latter are often obscured (Fig.11.4B). Slope oversteepening by late Pleistocene ice moving along the plateau edges, followed by deglaciation and withdrawal of ice support, favoured the slumping of large masses of basalt and chalk on slip planes provided by the Lias shales. The features are very well displayed at Garron Point (Fig.11.5) below Black Hill on the Antrim coast and below Binevenagh overlooking Lough Foyle. Although now stable, the slumped blocks show steeply tilted basalt, chalk and shale; weathering of the blocks gives rise to numerous active debris flows and mudslides, together with minor accumulations of talus and small landslips.

4.2. Debris flows

Debris flows constitute an important process of slope modification where slopes exceed about 25°. Compact glacial till, solifluction deposits and modern talus, under a variety of vegetation (except trees), have been shown to be unstable when subjected to high intensity rainfall of the order of 37-58mm/day (and even more so with rates of 5-11mm/hour), according to observations by Prior *et al.*(1970, 1971). Many upland areas in Ireland bear the scars of repeated debris flows, for example, valley slopes near Ardara and on the quartzite screes of Errigal Mountain (Co.Donegal), in Glenmacnass (Co. Wicklow), in the Mourne Mountains (Co.Down), the Galtee Mountains (Co.Tipperary) and near Leenane (Co.Mayo). Detailed studies in Co.Antrim and in Co.Londonderry indicate the widespread nature of debris flows: seventy occurred in north-east Antrim between 1966 and 1970, eighteen on the flanks of Binevenagh in 1966, involving 2050m^3 of debris (Fig.11.6) and eleven in Co.Sligo in 1968. While not life-threatening, the flows can occur suddenly, destroying vegetation and occasionally damaging or blocking roads.

4.3. Mudslides

Mudslides have developed where Liassic shales outcrop in old landslide blocks above the Antrim coast road between Larne and Carnlough (Figs.11.4B and 11.6). At Minnis

Fig.11.5. Aerial view of Garron Point, Co.Antrim, showing multiple rotational landslips, with vertical displacements of up to 125m, below the plateau surface at about 300m O.D. Some of the blocks have prominent steep seaward faces and back-tilted upper surfaces, while others have been degraded by weathering and their outlines obscured by aprons of block scree (Photo: *Aerofilms Ltd*)

North (Fig.11.7A), the mudslides are located on the lower slopes of a slumped block where the Lias shales have been weathered and reduced to lumps of stiff clay in a matrix of soft mud. The instability depends on hydration of the montmorillonite-rich clay derived from the weathered shale. The mudslide tracks below the bowls forming the source areas are generally developed in the Lias clay and glacial till which mantles the lower coastal slopes. The tracks supply mud directly on to the Antrim coast road which has been blocked or partially blocked on numerous occasions (ten times in 1971-72; Hutchinson *et al.*, 1974).

The mudslides are capable of surging forwards as undrained loading takes place on the flatter sections of the slide tracks: given the steepness of the mudslide front (about 30-35°), an abrupt discharge of mud can take place at high speed (up to 8m/minute) and

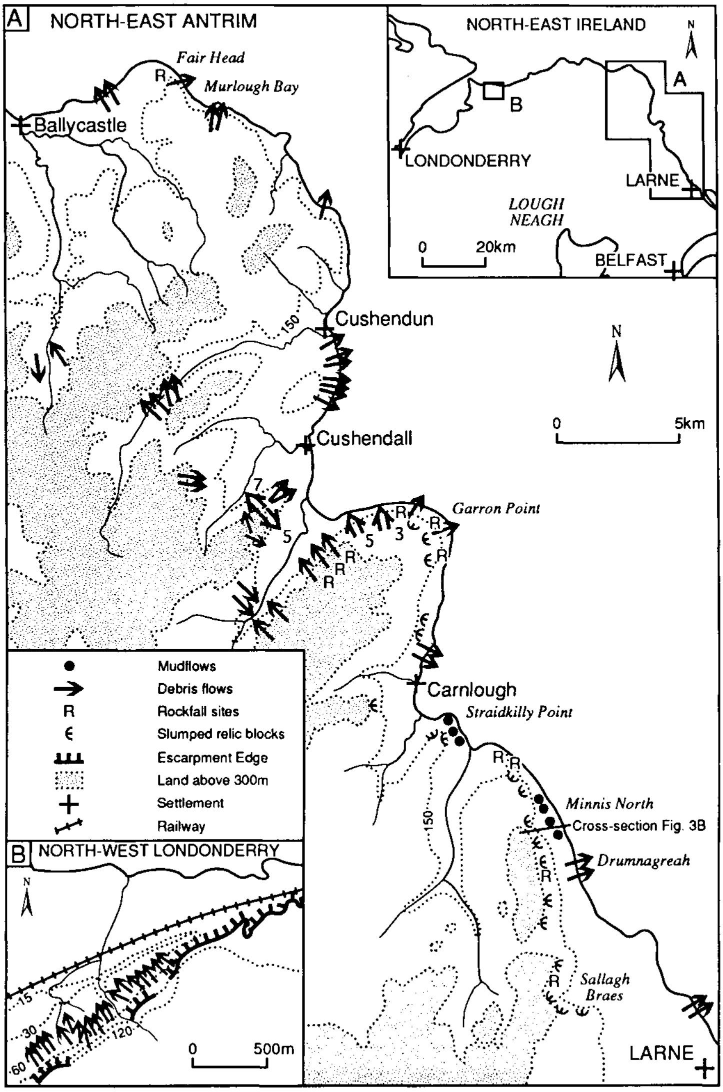


Fig.11.6. Mass movement sites in north-east Co.Antrim and north-west Co.Londonderry. Inset at top right shows location of the areas covered on maps A and B.

without warning. On 22 July 1972, the coast road was blocked to an average depth of 1.5m over an area of approximately 160m^2, representing an accumulation of over 4000t of mud. Another large mudslide took place on 24 November 1974 near Drumnagreagh

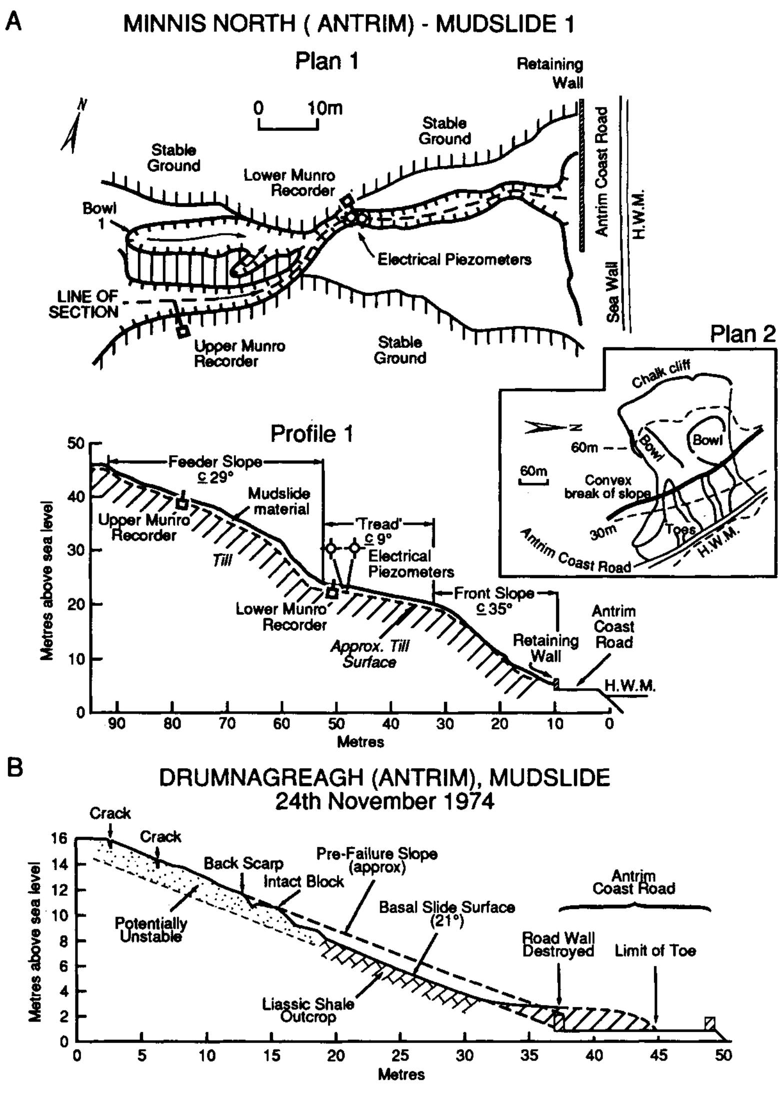


Fig.11.7. A. Minnis North, mudslide no.1 (Co.Antrim: for location, see Fig.11.6). The position of the Munro Recorders monitoring movement of the mudslide at two points, and the position of the electrical piezometers recording pore-water pressures on the accumulation tread of the mudslide are shown on Plan 1 and Profile 1. Plan 2 shows the four mudslides, together with their bowls (source areas) and tracks. The Antrim coast road cuts across their toes (after Hutchinson, Prior and Stephens, 1974).
B. Drumnagreagh mudslide, Co.Antrim (for location, see Fig.11.6), 24 Nov. 1974. The mudslide is shown having partially blocked the Antrim coast road (after Prior, 1975).

(Figs.11.6 and 11.7B; Prior, 1975). As at Minnis North and Straidkilly Point, the mechanism involved the development of critical pore-water pressures, generated by rainfall, in material involving large masses of Liassic mud on slopes exceeding 20-35°. The problem along the Antrim coast road has been exacerbated at times by road widening, cutting off the toes of the mudslides and artificially steepening the slope immediately above the road.

5. Peat bog flows

Peatlands cover about 15 per cent of Ireland, or approximately 12 000km^2, having formed during the last 7000-8000 years (Mitchell, 1976; Fig.11.8). Although there are many intermediate types, there are basically two sorts of peat bog.

Large *raised bogs* mainly controlled by the groundwater table are extensive across the poorly-drained Central Lowland, with a mixture of peat types and characteristic convex profiles (Mitchell, 1976). Occupying areas from a few hectares to many square kilometres, they average 6m in thickness, with a domed top rising perhaps 10m above the surrounding countryside. *Blanket peat bogs* depend on persistent rainfall (>1000-1300mm) and low evaporation for continued growth and are found on the mountains and plateaus where slopes are less than 15°, and especially where acid parent materials encourage growth. In the west, the increased rainfall (over 250 rain days per year) and high humidity allow acid blanket peat to form at lower altitudes, even down to sea level and on limestone bedrock. The presence of impervious glacial drift and high rainfall have also favoured extensive blanket peat formation on the basic basalt lavas of the Antrim Plateau, although initiation of peat growth was in places encouraged by Neolithic and Early Bronze Age farming practices which stimulated the development of podsols and waterlogging of the soils (Mitchell, 1976).

Both types of peat bog are susceptible to natural erosion (Kilroe, 1907). Bog bursts occur in many different topographical situations, while upland blanket peats also suffer from gullying and occasionally, at high altitudes, wind deflation. Figure 11.9 shows the distribution of recorded bog bursts during the last 350 years, based on a variety of sources including Colhoun *et al.*(1965) and Cruickshank and Tomlinson (1990). The flows of wet peat can occur suddenly and without warning, but generally reflect rapid additional precipitation or snowmelt on an already saturated bog, upsetting its stability. Springs within the interior of many bogs, peat cutting and drainage at the bog margins and breaks-of-slope in and around the bog which affect drainage and tension within the peat mass, may also be important in destabilising the bog. Mitchell (1938) has suggested that failures in the blanket peat may have sometimes resulted from actual peat growth, rendering it unstable. Bursting may help to restore equilibrium and is part of a cycle when peat rests on a sloping surface of rock, glacial till or some other type of impermeable regolith. Table 11.1 gives some examples of notable peat bog bursts in Ireland.

Extremely high amounts of rainfall over short periods undoubtedly contribute to peat bog failures. In Co.Sligo it is estimated that 81 000m^3 of peat erupted from an upland

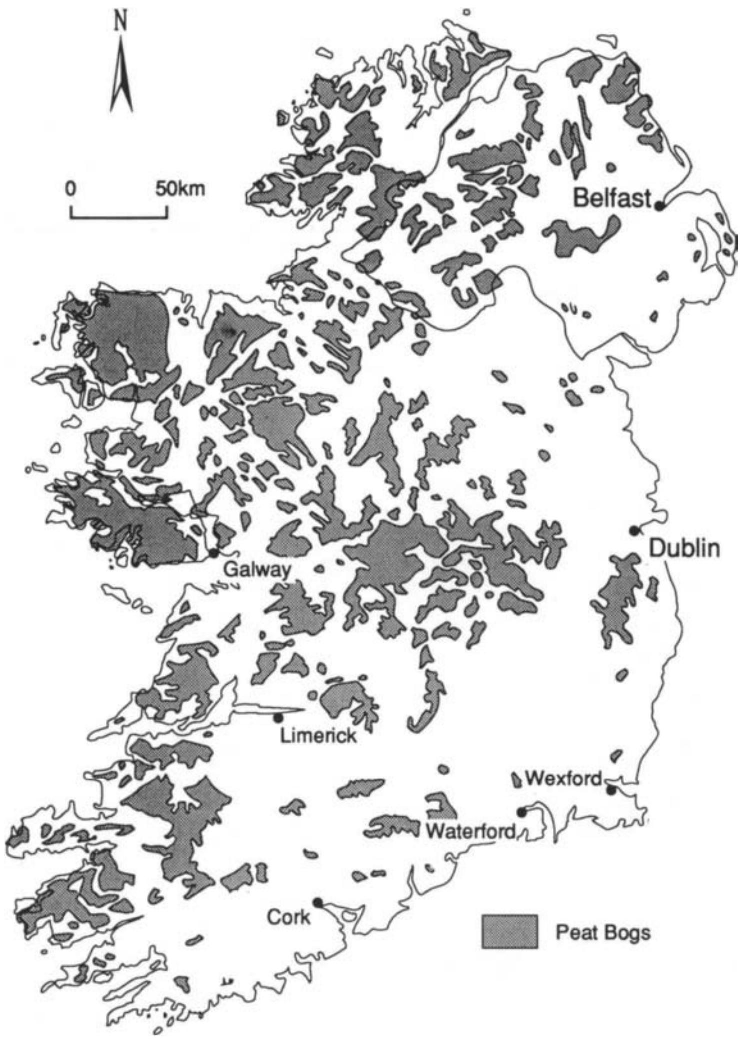


Fig.11.8. The distribution of blanket peat bogs and raised peat bogs in Ireland (after Orme, 1970)

blanket bog in 1984 (Alexander *et al.*, 1986), corresponding to about 4200t of peat and 73 700t of water on the basis of bulk density and moisture content analysis. Five river crossings were blocked, there were forestry losses and 40ha of farmland were inundated. Previous burning of the bog surface and a succession of dry summers may have led to cracking of the bog surface, allowing erosion by gullying to take place; in turn, this may have contributed to the instability.

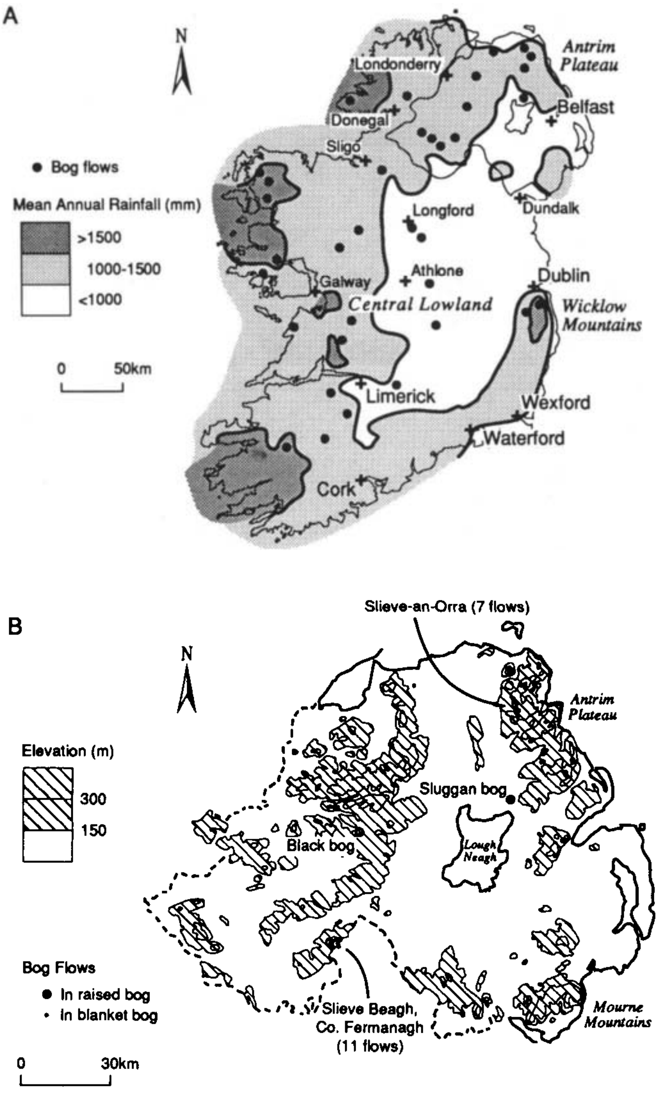


Fig.11.9. A. Recorded peat bog flows in Ireland, and generalised distribution of mean annual rainfall (after Colhoun *et al.*, 1965, Cruickshank and Tomlinson, 1990, and other workers).
B. Distribution of peat bog flows in Northern Ireland up to 1980: note the concentrations of sites on the Antrim Plateau and Slieve Beagh, Co.Fermanagh (after Cruickshank and Tomlinson, 1990)

Table 11.1. Major peat bog bursts in Ireland (see also Fig.11.9)

Year	Location	Comments
1708	Castlegarde Bog, Co.Limerick	6m deep in places, flowed for several km along a valley.21 deaths reported.
1819	Owenmore valley, Ennis, Co.Mayo	January. Some loss of life.
1883	Between Moor and Baslick, near Castlereagh, Co.Roscommon	25 January. Peat covered 16km^2 of agricultural land.
1896	Knocknageehan Bog, Owenacree valley, Co.Kerry	120ha of agricultural land devasted by an estimated 5 million m^3 of peat. Some loss of life.
1931	Glencullin, Co.Mayo	February. See Delap (1932)
1938	Powerscourt, Co.Wicklow	July. See Mitchell (1938)
1945	Glen valley, Meenacharry Townland, Co.Donegal	January. See Bishop and Mitchell (1946)
1963	Glendun, Co.Antrim	November. Damage to agricultural land (Colhoun *et al.*, 1965)
1979	Carrowmaculla, Co. Fermanagh	November. See Tomlinson (1981b)
1980	Slieve-an-Orra hills, Co.Antrim	Seven bog flows in blanket peat, damage to forestry. See Tomlinson and Gardiner(1982)
1984	Straduff Townland, Co.Sligo	18 October. Damage to farmland and forestry. See Alexander *et al.*(1986)
1985	South-east Co.Sligo and south-west Co.Leitrim	See Alexander *et al.*(1985)

In 1980, on the Slieve-an-Orra hills of the Antrim Plateau, seven bog slides occurred in blanket peat resting on impervious glacial till, as a direct result of a thunderstorm that produced 47 and 97mm of rain respectively at two nearby autographic gauges in 45 minutes. The slides were probably related to the drains cut in the blanket peat before planting of Sitka spruce forest (Tomlinson and Gardiner, 1982).

In their comprehensive survey of the peatlands of Northern Ireland, Cruickshank and Tomlinson (1990) indicated that erosion of the peat is widespread in the blanket bogs, except in the far west of the Province. Gullying, the development of anastomosing channels leaving tiny islands of peat, the production of peat hags and the presence of funnel-shaped bog flows all testify to continued loss of peat cover, which is also accelerated by continued cutting and reclamation. Detailed examination of peat erosion in the Mourne Mountains, on the Antrim Plateau and in the Sperrin Mountains indicates that sub-surface piping may aid initiation of deep erosion channels. Field evidence, analysis of pollen recovered from the peats and the evidence from climatic records suggest that erosion began after about 1750-1835, and that peat bog bursts have tended to occur during wetter summers and wetter autumns during the period 1730-1980 (Mitchell, 1976; Tomlinson, 1981a). Undoubtedly, many old flows have gone unrecorded in Ireland, and have now healed or been removed by peat cutting, but the surveys provide a useful record of this phenomenon and there can be little doubt that bog bursts will continue to occur. No other single geomorphological hazard has caused such damage and loss of life in Ireland in the past, and it is doubtful if any other country in Europe is affected by this hazard on such a scale.

6. Coast erosion

There is a fundamental contrast between the generally rugged rocky and cliffed coast of the west of Ireland and the mainly drift-clad Irish Sea coast south of Belfast Lough. Both the morphology of the coastline and the rates of coastal erosion are closely related to the geology; Figure 11.10 shows data on erosion rates based on the work of Carter and Bartlett (1990), Davies and Stephens (1978), Johnston (1981), McGreal (1976), McGreal and Craig (1977), McKenna *et al.*(1992), Orford and Carter (1982) and Stephens (1970, 1985).

While erosion rates for soft-rock coasts (drift, sand dunes, etc.) can be given with some confidence, the same does not apply to rocky coasts. Although there may be clear evidence of change over time in cliff and rock platform profiles, often from comparison of dated photographs, only crude estimates of rates of cliff retreat can be made. Consequently, the differentiation of the symbols for bedrock erosion used on Figure 11.10 must be regarded as only tentative. On the other hand, field observations readily identify unstable rock cliffs where fresh scars indicate continued collapse, though not all of these are exclusively the work of the sea alone (Mitchell, 1989, on Valencia Island, Co.Kerry).

On the Antrim coast, rockfall activity involves both Tertiary basalts and the underlying chalk, the latter being very susceptible to present-day freeze-thaw action, as can be observed at Garron Point and near Glenarm where remedial engineering works have been necessary to protect the coast road. Monitoring of the basalt cliffs at Ardclinis, on the north flank of Garron Point, demonstrated the intricate relationship between the failure of the various lava layers and their physical and chemical properties (Prior *et al.*,

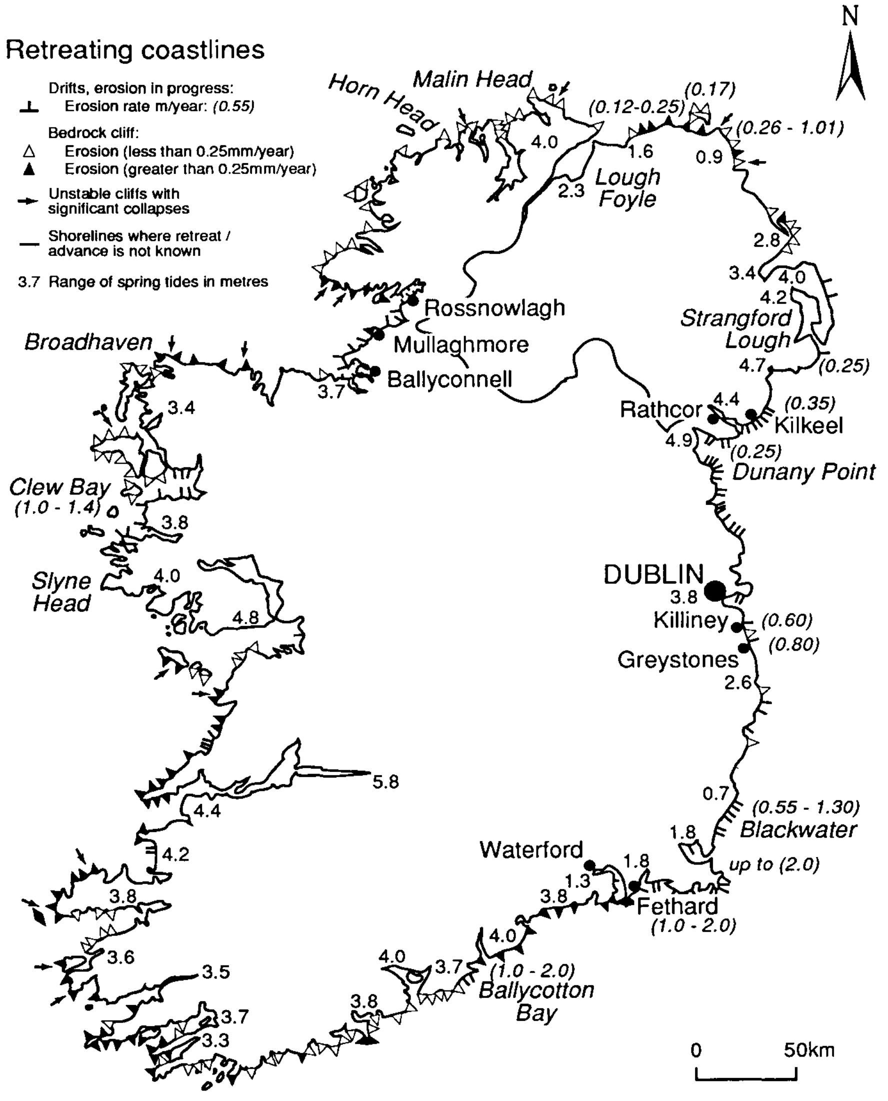


Fig.11.10. Coastal erosion in Ireland. Note that numbers inland refer to the range of spring tides (metres); numbers in brackets in sea areas refer to rates of coastal erosion (metres per year). Compiled from many different sources (see text).

1971). At Fair Head, occasional falls of massive prisms of dolerite (Fig.11.11) and a constant accumulation of shale fragments indicate the degree of cliff instability. Disintegration of parts of the chalk cliffs at Garron Point from time to time also produces rockfalls with blocks up to $36m^3$. Other massive falls have been recorded in the basalts at Binevenagh and Downhill, and on the Giants Causeway cliffs (McKenna *et ai.*, 1992).

The cliffs in glacial drift along the Kilkeel-Carlingford coast are up to 15m high and retreating at between 0.25 and 0.35m/year (McGreal, 1979). Direct wave attack is aided

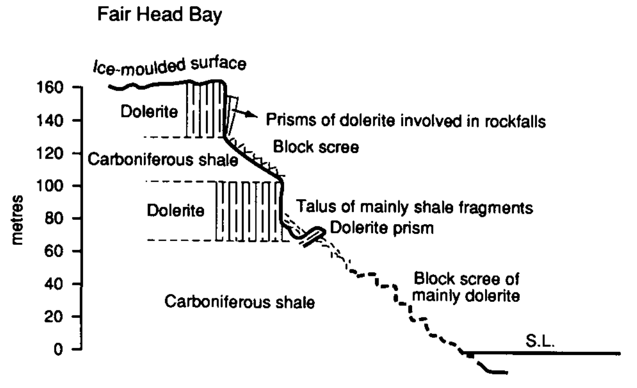


Fig.11.11. (*upper*) Diagrammatic cross-section at Fair Head, Co.Antrim (for location, see Fig.11.6). The twin dolerite sills are intruded into Carboniferous shales. The upper of the two dolerite outcrops shows fresh scars where huge prisms of rock have been dislodged to form a large part of the block scree extending to below sea level; one large prism fell in 1970 and there is a constant stream of falling shale fragments (after Davies and Stephens, 1978).
(*lower*) View showing the fallen dolerite prism in 1970, embedded in the block scree; the scale is provided by Dr Francis M. Synge. (Photo: N.Stephens)

by groundwater moving seawards through the varied drift materials and producing slumping where it emerges on the cliff face. Similar processes are at work farther south; at Killiney and Greystones, the former cliff-top railway had to be moved and re-aligned inland in this century as erosion proceeded to destroy the protective sea wall, the remains of which may now be seen separated by up to 10m from the modern cliff. At Mizen Head, at the southern end of Brittas Bay, a thirteenth to fourteenth century mediaeval moated site has been partly eroded away by the sea (Mitchell, 1990). At Blackwater, the old road leading to the beach has been abandoned, a farm is being threatened by the receding cliff and field boundaries are seen to be truncated at the cliff edge in a haphazard manner. Significant collapses of cliff sections 15m high in glacial and periglacial deposits have occurred near Fethard, mainly owing to basal undercutting. Other data on coastal recession are given in Johnston (1981), McKenna *et al.*(1992), Orford (1988) and Orford and Carter (1982), the last of these being concerned with barrier-bar changes in south Wexford.

Serious losses of farmland have been recorded at Garryvoe in Ballycotton Bay, Co.Cork (Fig.11.12A). The cliffs, 3m high in glacial drift, have receded about 145m in approximately 110 years. In Clew Bay, Co.Mayo (Fig.11.12B), the drumlin swarm formerly extended at least to a line from Mulrany to Louisberg, and possibly to Roonah Quay. On a conservative estimate, at least 10km of drumlins have been removed by erosion since the sea achieved approximately its present level about 3000BP. Many of the remaining drumlins exposed to the Atlantic waves show west-facing cliffs 10-30m high, while among them a complex series of spits and tombolos has been built (Guilcher, 1962; Synge, 1968; Davies and Stephens, 1978).

In Blacksod Bay and Broad Haven, cliffs 1-2m high in blanket peat are suffering erosion where the peat extends below low-water mark. The future evolution of this area remains problematical, as it does around Horn Head in Co.Donegal where mobile sand dunes have long been a threat to adjacent farmland.

At the entrance to Lough Foyle, there has been an increase in erosion of the marine and aeolian sands forming Magilligan Foreland (Carter and Bartlett, 1990): this has been related to an increase in the number of storms and northerly on-shore winds. In addition to the problems likely to be faced if sea level continues to rise, the northern and western coasts of Ireland are among the windiest in the British Isles, with up to 40 days per year experiencing gales (winds exceeding 65km/hour); hourly mean wind speeds can attain 125km/hour and gusts up to 200km/hour, with 50-year return periods (Perry, 1981). Such wind strengths amplify the power of Atlantic waves, increasing the threats from coastal erosion, coastal flooding (linked to wind-driven surges) and coastal landslides, and causing loss of or damage to forest plantations. The average height of North Atlantic waves has increased since about 1963, and storm events have become more frequent in the late 1960s, 1970s and early 1980s, creating conditions where particularly fragile coastal segments are put at risk.

As is well known, coastal erosion and deposition can operate within short distances of one another, sediment movements taking place in a cellular manner. Interference by man in building sea walls, groynes and other structures, and in dredging and extracting

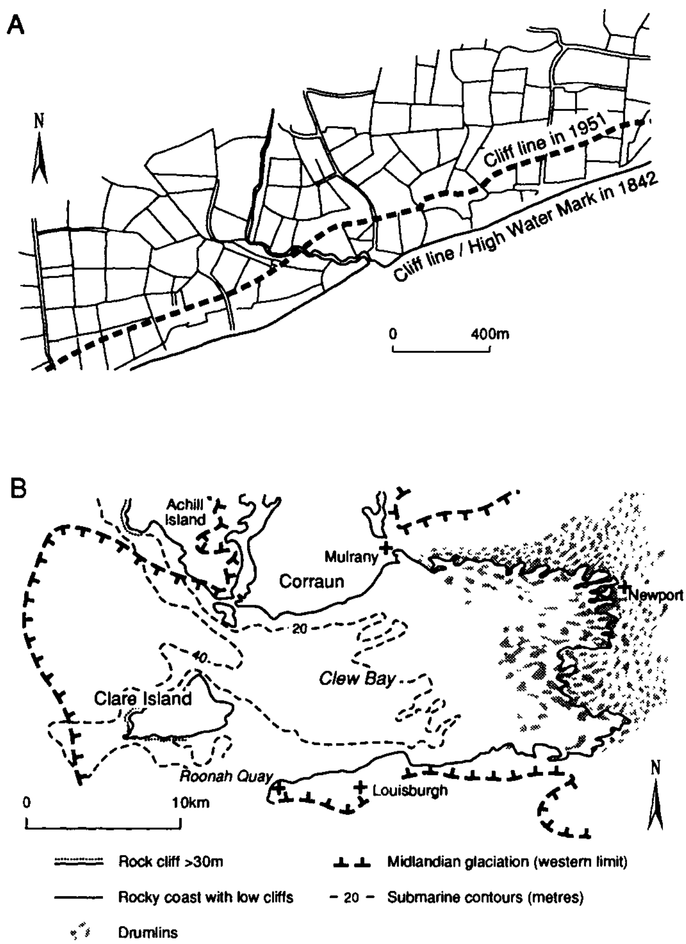


Fig.11.12. A. Coastal recession in glacial drift at Garryvoe, Ballycotton Bay, Co.Cork, between 1842 and 1951 (based on Ordnance Survey of Ireland maps and air photographs)
B. Erosion of coastal drumlins in Clew Bay, Co.Mayo, during the last 3000 years (after Synge, 1968, and Davies and Stephens, 1978)

sand, shingle and seaweed can contribute significantly to the instability of beach systems. Along the north coast, Carter and Bartlett (1990) calculated that extraction of beach sediment amounts to 10 000m^3/year; elsewhere it may be only a few cubic metres a year, as observed on many pocket beaches, for example, in Co.Wexford and particularly in Co.Galway where "soil" has been produced on bare granite surfaces in this way. Whatever the amount involved, the long-term loss to beach and dune systems can be serious if there is no replenishment from rivers or streams. Likewise, there are many coastal sites where recreational activities have created severe problems in terms of damage to the beaches and to fragile vegetational communities on sand dunes (Brady *et al.*, 1972).

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ITALY

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1. Introduction: the geodynamic and structural pattern of Italy

Italy is well known as a country affected by many natural hazards which have frequently caused disasters. Since ancient times, there have been numerous records of calamities resulting in death and destruction: there can be no-one who has not heard of Pompei, Ercolano, Stabia and Oplonti where whole communities were destroyed by ash from Vesuvius, the volcano near Naples whose eruption in 79 A.D. was described by Pliny. The horrendous effects of earthquakes and the devastation that they have caused throughout Italian history are also well known. The greatest, in the Calabrian-Sicilian area around the Messina Straits in 1908, killed no less than 85 000 people; the most recent was that of December 1990 in Sicily. The enormous damage caused by flood disasters such as that of the river Arno in Florence (Firenze) in 1966 is still fresh in the public mind, as are landslide catastrophes such as the collapse of the mountain side into the Vajont reservoir in north-eastern Italy in 1963, causing a wave of water to overflow the dam and drown 2000 people in the valley below.

Besides being a land of extreme events and immense natural disasters, Italy is also a land where there is a persistent risk from the cumulative effect of thousands of minor events or slowly-acting processes which in the long run cause similar amounts of damage. The roots of this lie in the geological and geomorphological instability which is derived from a combination of endogenic and exogenic factors.

Italy has two great mountain ranges of Tertiary age: the Alps which close off the country to the north in an arc which stretches from the border of France in the west to Slovenia in the east; and the Apennines which form the north-south spine of the Italian peninsula as far as Sicily. These were produced by the Alpine orogenesis involving the collision between the European and African plates (Fig.12.1). In more detail, the Mediterranean area is built of a series of micro-plates resulting from the associated compressional and tensional stresses, a crustal mosaic which involves Italy and within which relative movement is still taking place. Only the remnants of the African foreland, the areas of Puglia and Iblei (Sicily), appear to be comparatively stable, as is the island of Sardinia, the only major Hercynian (and Caledonian) fragment in Italy. However, this seems to be a block which also shifted in the Neogene, rotating anti-clockwise to its present position. The Italian peninsula itself appears to have rotated from west to east, leaving behind it the extensional basin of the Tyrrhenian Sea with its ocean-like characteristics. The Adriatic margin of the Italian peninsula is, in contrast, still undergoing compression.

A further contributor to the present tectonic instability of Italy is isostatic adjustment which is far from complete, as can be seen from the intensity of vertical uplift in many

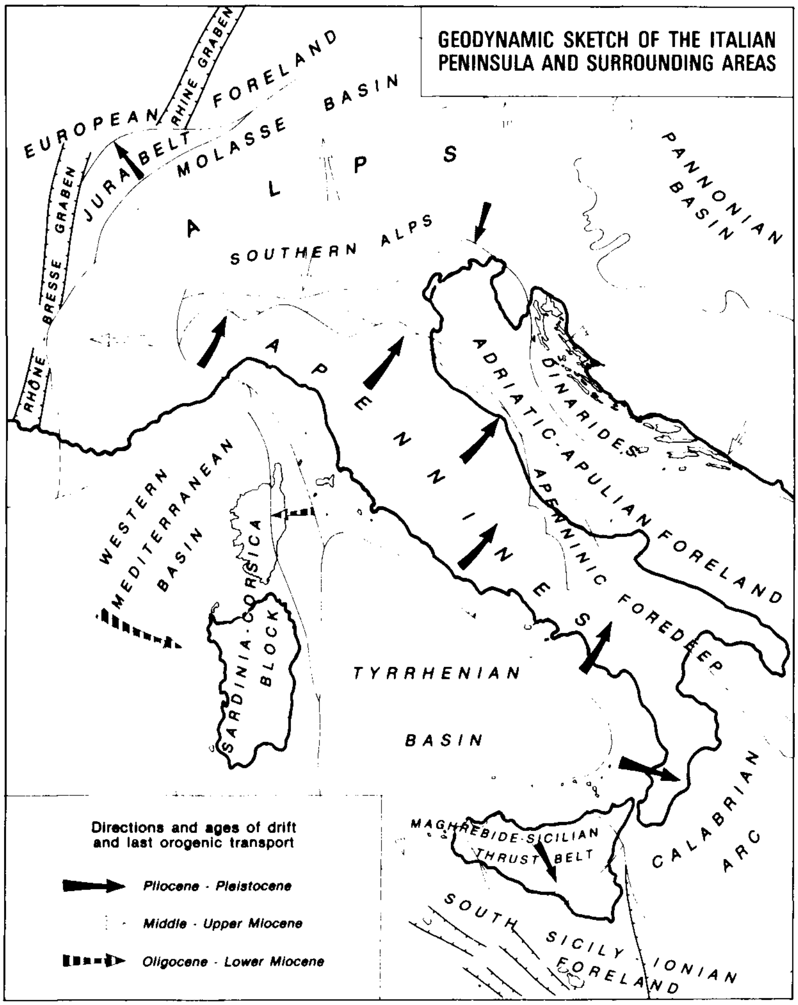

Fig.12.1. General structure and tectonics of Italy and surrounding areas (from CNR, Progetto Finalizzato *Geodinamica*, Modello Strutturale d'Italia, S.EL.CA., 1990)

places. The present geodynamic activity of Italy thus results from continuing endogenic processes acting on a structure of great complexity (*Societa' Italiana di Mineralogia e Petrografia, 1980)*.

Exogenic processes operating on this tectonic background have combined to produce strongly articulated relief and to generate, in many localities, exceptional relief energy. The strong relief is mitigated only in certain areas by terrestrial sedimentation from the late Tertiary onwards, and by Quaternary marine transgressions, which have given rise to landscapes of either plains or low relief. Plains cover only 23 per cent of Italy, but they have become the areas of the greatest concentrations of economic activity and of the Italian people; in places, the population densities reach 190/km^2. The plains consist of either coastal strips or the classical valley basins. The largest of these, the Po Plain, is the internal part of the basin of the river Po, with its exceptionally deep (over 6000m) infill of recent marine and continental sediments. Its flat surface conceals the fact that the folds of the Alps and the Apennines, mountains which externally surround the plain, continue and unite deep below it.

Many exogenic processes are at work on this dynamic and unstable land which has such great variations in relief and geology. Weakly-cemented and very degradable sedimentary formations (of both orogenic and post-orogenic age) are widespread. The range of exogenic processes reflects the range of climates, whose variety is surprising in such a medium-sized country (301 000km^2). However, it must be remembered that Italy extends over more than 10° of latitude, and that elevations vary from sea level to 4810m (Mont Blanc) in the Alps and to 2918m (Gran Sasso) in the Apennines. The mountain ranges, furthermore, vary in their orientation with respect to air flows. The coastline stretching through thousands of kilometres is highly indented, and the surrounding seas (Fig.12.2) have different temperature characteristics. It then becomes clear why there are so many varying combinations of air temperature and precipitation, producing climates ranging from sub-tropical (Köppen's C) to nival (E). In conclusion, climatic variability and endogenic activity are the basic factors that control the exceptional instability of the Italian landscape, to the extent that Italy may be considered the ideal place in which to study nearly every type of geomorphological hazard (Castiglioni, 1976; Martinis, 1987).

2. Endogenic processes

2.1. *Seismicity and seismic hazards*

Orogenic and isostatic movements continuing from the Tertiary to the present-day mean that Italy is an area where the concept of neo-tectonics is important and fundamental (Baratta, 1901). Whole areas are being subjected to tectonic uplift or subsidence in blocks bounded particularly by normal faults. There is also transcurrent movement but this is often more difficult to demonstrate. There has been considerable progress in the study of faults presumed to be "active", especially since the recent major

Fig.12.2. The regions of Italy

earthquakes in Friuli (1976) and Campania-Basilicata (1980), but much remains to be done.

The seismic hazard in Italy can be clearly appreciated by consulting the Catalogue of Earthquakes in Italy from the year 1000 to the present, published by the National Research Council (CNR), which records a lengthy sequence of seismic disturbances of all levels of severity (Carrozzo *et al.*, 1973). It must be remembered that, over and above the damage to property (and the associated personal injury and deaths) directly caused by the seismic waves, there is also the secondary damage resulting from soil liquefaction and from gravitational movement, particularly landslides, which are also a real hazard in Italy. During the Friuli earthquake (1976), for example, there were more than 1000 landslides, mostly falls; in the Campania-Irpinia earthquake of 1980, large rotational slides were more common (Brisighella et al., 1976; *Consiglio Nazionale delle Ricerche*, 1977; Postpischl *et al.*, 1985). In both, it was often the case that ancient landslides were reactivated in areas which subsequent microzonal investigations revealed were characterised by faults.

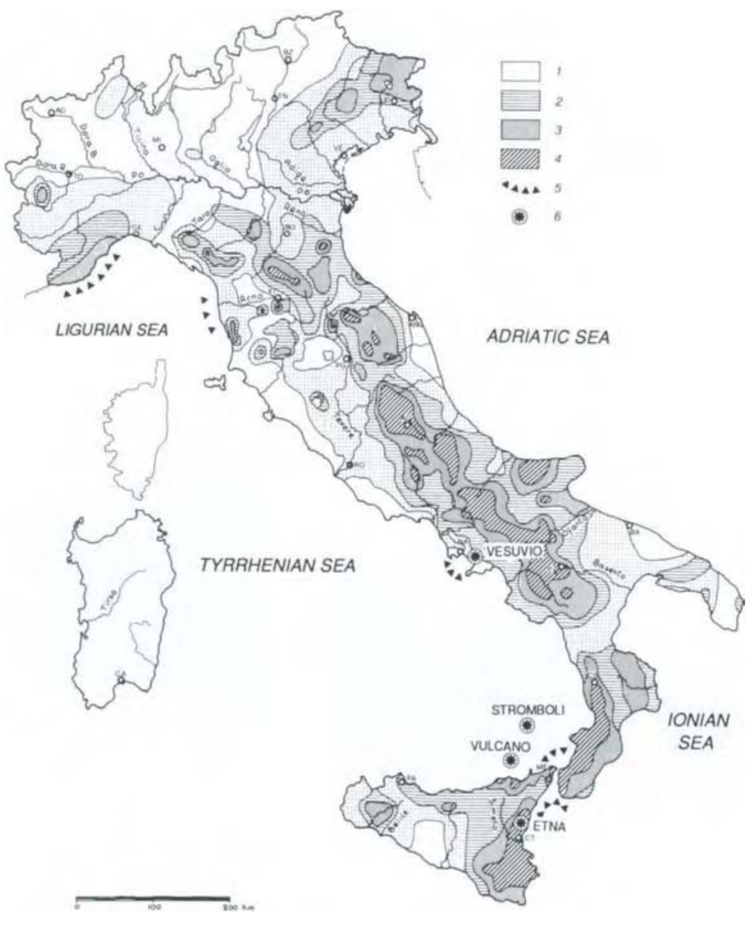

Fig.12.3. Seismic and volcanic activity in Italy, showing areas of maximum earthquake intensity on the Mercalli scale: 1: ≤ VII; 2: VIII; 3: IX; 4: ≥ X; 5: coastlines most likely to be affected by tsunamis; 6: active volcanoes

For some time now, a classification of the country into seismic zones has been in progress (*Consiglio Nazionale delle Ricerche, 1980*). The most recent classification by the CNR in 1981 - the *Progetto Geodinamica* - is based on the maximum seismic intensity recorded from the year 1000 to the present, and on the intensity corresponding to the recurrence interval of 500 years. Figure 12.3 shows that almost all of Italy is subject to some level of seismic hazard, with the exceptions of Puglia and Sardinia. The areas of greatest risk are in Calabria, particularly near the Straits of Messina, in the Irpinia district (between Campania and Basilicata), in Abruzzi, in the Marche hinterland, in Garfagnana and Mugello (Tuscany), in Friuli and in western Liguria. Unfortunately, however, nearly every region has a history of tragic catastrophes, and even areas which are not considered seismic, such as the Belice valley in western Sicily, can become involved, as in 1967 when 300 people were killed (Bosi *et al.*, 1968). The most recent earthquake in December 1990, which once more claimed the lives of many victims and caused extensive damage, hit the south-west of Sicily, well known for its seismicity.

In this century there have been twelve disasters. Apart from the considerable damage to buildings and monuments, the Reggio Calabria-Messina earthquake of 1908 resulted in 85 000 to 100 000 deaths, the earthquake in Marsica (Abruzzi) in 1915 saw the loss of 30 000 lives, in Friuli in 1976 (Fig.12.4) the victims numbered 1000, and in Campania-Irpinia in 1980 there were 4000 deaths.

Fig.12.4. a) (left) Buildings damaged by the Friuli earthquake of 1976; b) (right) Effects of the Fruili earthquake, 1976: in the foreground, a damaged church and cemetery; in the background, rockfalls from the limestone mountains (photos: G.Rodolfi)

Lastly, some coastal seismic areas are also at risk from tsunami, which can cause disasters such as the one in Reggio Calabria in 1908. Among the areas at risk (Fig.12.3) are western Sicily, many parts of the Calabrian coast, the Gulf of Naples, the Conero (Marche) headland and western Liguria.

2.2. *Volcanism*

Italy is a country where volcanism has been continuous since the Tertiary era. Furthermore, the peninsula (and even Sardinia) owes a great part of its morphology to the activity of numerous volcanoes over periods of varying length and with different intensities, related to the Apennine orogenesis and to the Tyrrhenian crustal extension. The type of activity ranges from the intracrustal acid magmatism of Tuscany to the continental basaltic volcanism of Sardinia, and includes various intermediate types. Sometimes, volcanic activity ended long ago; elsewhere it continued until a few centuries ago, but in both cases it is now only recorded in interesting morphological features. There are, however, four sites where volcanoes are still active and a real volcanic hazard exists; additionally, there is the Campi Flegrei which, though considered dead, has recently been the cause of great concern (Corrado *et al.*, 1980; Rosi and Sbrana, 1987).

Two volcanoes, Stromboli and Vulcano (Fig.12.3) are islands in the Eolian arc off northern Sicily; they arose in the mid- to late-Pleistocene period following calc-alkaline and then shoshonitic activity.

Stromboli is a large strato-volcano emerging from the floor of the Tyrrhenian Sea and reaching a height of 926m above sea level (c.3000m from the sea floor). Although it has been continuously erupting lava for thousands of years, it causes very little concern since the material emitted runs into the Sciara del Fuoco, a vast gap that was formed by deep-seated deformation in the side of the volcanic cone. On the other hand, its explosive character can be a danger because during major eruptions, pyroclastites can be ejected some distance, causing damage to crops and injury to inhabitants.

The island of Vulcano consists of several superimposed structures. Its past eruptions have also been phreato-magmatic and always explosive. This is, therefore, an area where the inhabitants are subject to volcanic risk.

The features of Etna, a true giant among volcanoes with its height of 3270m and perimeter of more than 150km (Fig.12.5a), are more complex (Romano, 1982). It has more than 260 eruptive points, many of which remain in the form of eccentric conelets aligned along presumed fault lines, and it comprises several superimposed strato-volcanic structures. In the past there have been disastrous lava flows, as in 1928 when the town of Mascali was buried. The prolonged and impressive activity of this volcano in 1983 and 1992, the damage that was caused, and all the various attempts to arrest or divert the most dangerous lava flow, will be clearly remembered.

But the danger from Etna is as nothing when compared to the devastation caused by Vesuvius, perhaps the most famous volcano in history (Barberi *et al.*, 1990; Rosi *et al.*, 1980-81; Sheridan and Malin, 1983). At its foot and all around it there is a concentration of over 4 million people today (Fig.12.5b), constituting the district of Naples, which has

Fig.12.5. a) (left) Mt Etna, the biggest volcanic structure in Europe seen from a recent lava flow near Catania; b) (right) Aerial view of the Vesuvio-Somma volcanic structure. Note the density of settlements around the base (photos: G.Rodolfi).

grown up in spite of the destruction of the Roman city nineteen centuries ago and the damage that it has caused from that time up to 1944, the year of the last eruption.

Naturally it is the type of eruption that conditions the risk and from this point of view Vesuvius, rising to 1277m directly from the plains of Campania, presents danger from the possible effusion of lava and the emission of pyroclastic materials, giving birth to lahars when mobilised by water and, most dangerous of all, nueés ardentes. The Somma-Vesuvius (to give it its correct name, since the present Vesuvian cone started to form inside a caldera which originated from the collapse or destruction of an older edifice) is a classic "enclosed" volcano of an essentially explosive nature. Maps have been compiled of the risk entailed, using studies of all known eruptions. It is clear, though, as regards the danger from nuées ardentes, that the force and direction of the winds at the time can also play an important role (Fig.12.6).

2.3. *Subsidence*

Land subsidence is usually a slow process which is not always easy to interpret in terms of causes and which is often difficult to quantify. In certain areas of the Italian plains, however, it has recently become a serious threat, leading to damage to important historical buildings. It is necessary to emphasise the fact that all cases of subsidence have been greatly aggravated by human activity.

An outstanding example is that of Ravenna (Selli and Ciabatti, 1977), a city which has seen its splendid Byzantine churches gradually sinking after an increase in subsidence which, during the years 1953-73, amounted to ten times the average rate (2.6mm/year) recorded for the period 1885-1953 as measured from several points. The cause has been traced to the extraction of groundwater for a nearby industrial estate.

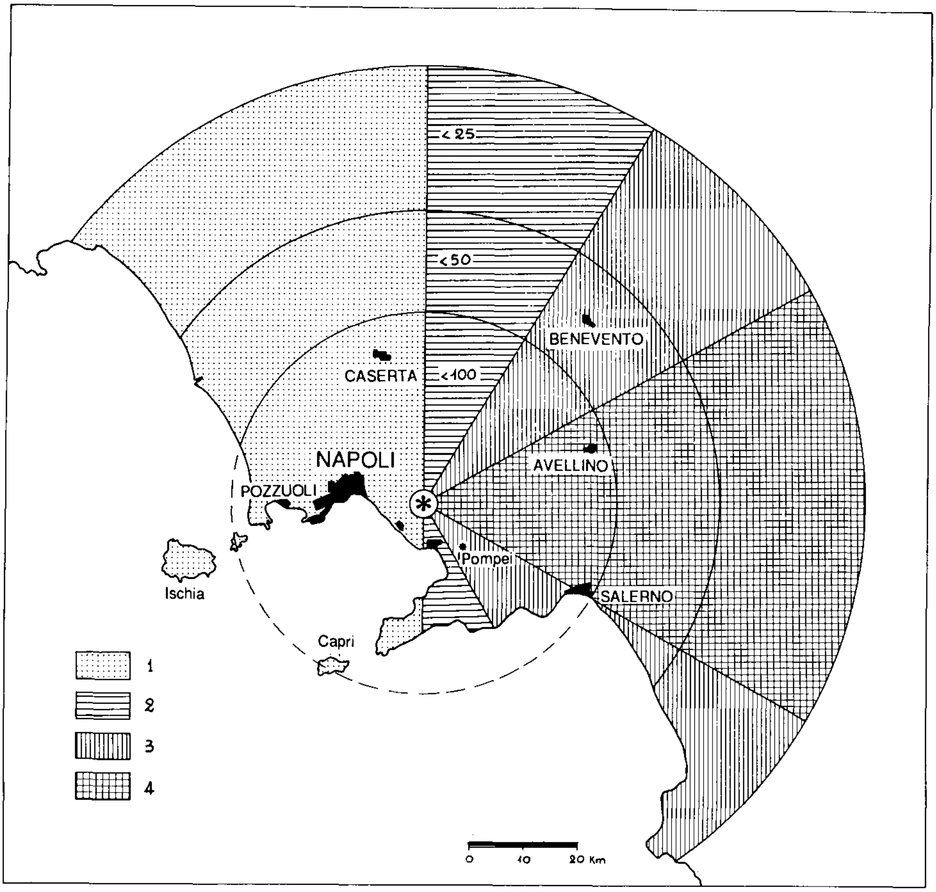

Fig.12.6. Map of the hazard from pyroclastic deposition according to thickness (25-100cm) in the Vesuvian area, compiled from data on all known Plinian eruptions of the volcano. The hazard scale increases from 1 to 4 (modified from P.Fazzini, 1985)

The same has happened in Venice (Gatto and Carbognin, 1981). The pumping of water for industrial use on an adjacent area of firm ground, and for domestic use in the city itself, has lowered the water table by 20m. This, together with other factors (of which the most important is the global rise in sea-level) has caused an increase in the frequency of events known as "high waters" when the famous city and its monuments such as the floor of the precious San Marco Basilica are periodically submerged. Subsidence has been calculated to have reached 10mm/year, but it is important to note that the gradual closure of numerous city wells and boreholes in the industrial area has resulted in a significant slowing-down of the rate of subsidence.

Positive results are also expected from similar measures taken in Pisa to counteract the progressive tilt of the famous Leaning Tower. On the outskirts of the town there are examples of man's influence on this subsidence. Near the Aurelia trunk road, subsidence

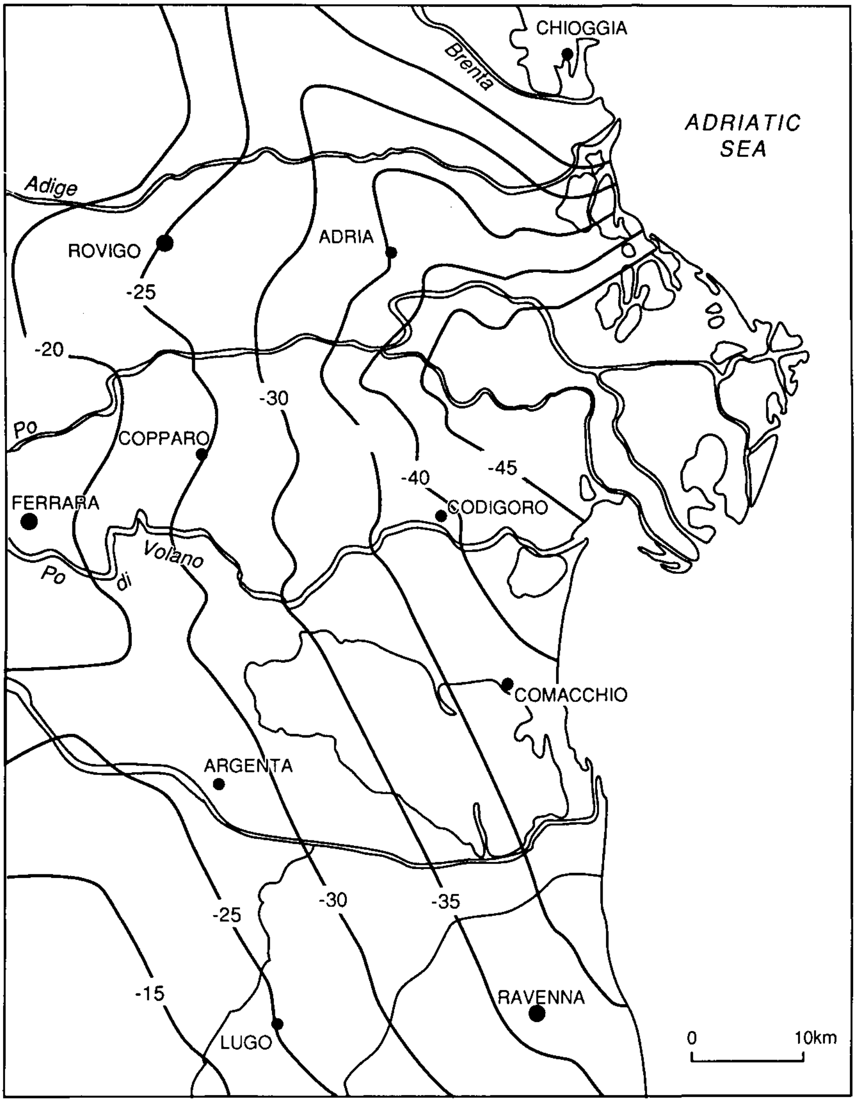

Fig.12.7. a) Subsidence of the Po delta, 1900-1957. Isolines are in centimetres (from M. Caputo *et al.*, 1970)

reaches 10mm/year whereas the normal rate for the Pisa plains and those around Versilia nearby is about 1.5mm/year. In the Pisa plain, there are the additional dangers of flooding and, more directly the result of subsidence as well as the impermeability of

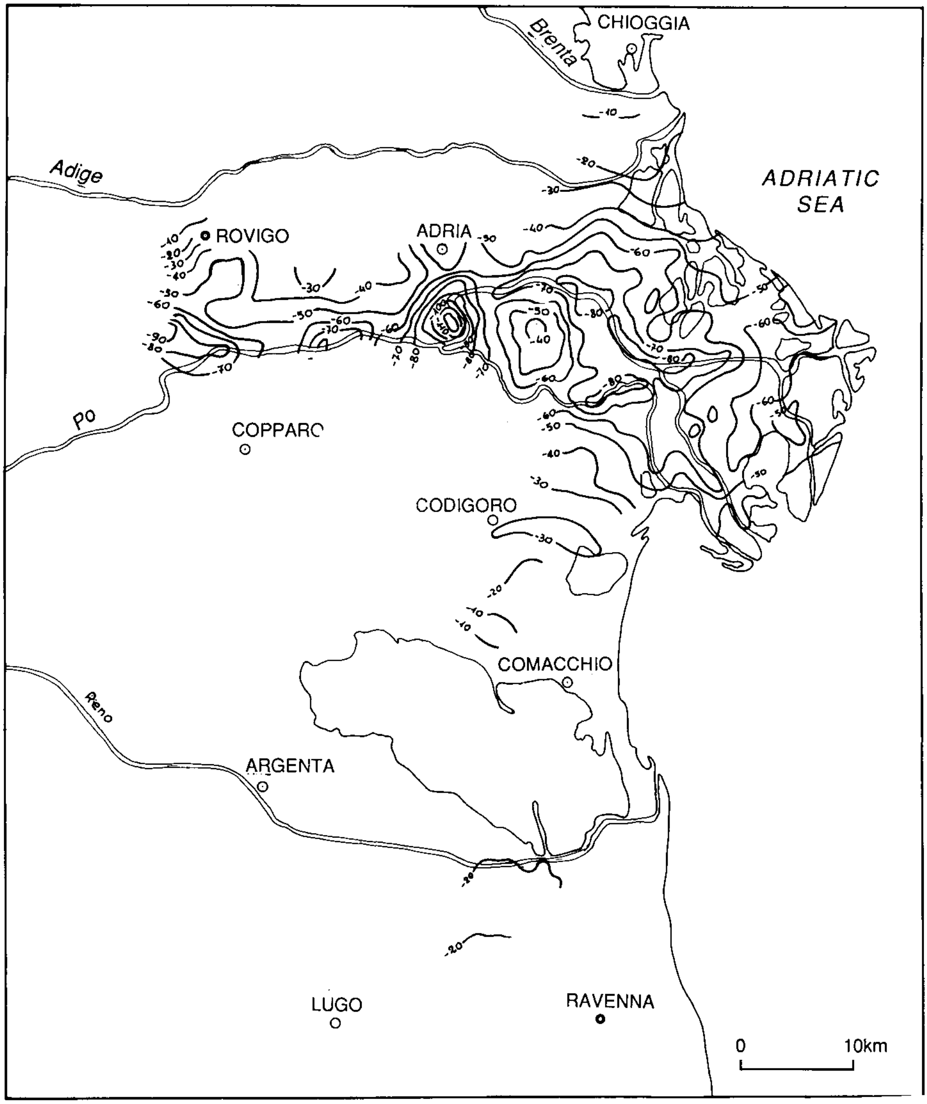

Fig.12.7. b) Subsidence of the Po delta, 1958-1967. Isolines are in centimetres (from M. Caputo *et al.*, 1970)

the substratum, the accumulation of stagnant waters in the town and its surrounding countryside.

The case which has been the subject of more debate than any others, however, is the delta of the river Po (Bondesan, 1989) protruding into the Adriatic Sea (Fig.12.7a, b). There are many wells in this area because of the presence of numerous methane gas fields. Subsidence here has accelerated considerably since the 1950s, as comparison of Figures 7a and 7b will show. While the isolines for the years 1900-1957 show subsidence of -45cm in the area within the apex of the delta, the map for the period 1958-67 shows both a more random pattern and higher rates, reaching as much as -110cm, representing an average increase of 12-13 times. It is well known that extraction of gas also entails the expulsion of considerable amounts of groundwater, and the removal of large quantities of liquid under pressure has been blamed for this abnormal increase in the rate of subsidence. The gradual closure of several gas wells has, in fact, improved the situation, but at the same time, part of the Po delta which was reclaimed from the sea with much effort in the past is showing signs of irreversible submergence beneath sea water.

The adverse consequences of ground subsidence in populated areas, nearly always owing to excessive groundwater pumping, are evident in many areas from the relatively high Modena and Bologna plains to the coastlands. There is an additional risk when excessive pumping of groundwater occurs in coastal areas, and that is the danger of salt-water intrusion. The main damage in this case is to crops.

One particularly unusual case of change in surface elevation, not to be confused with those already mentioned, is in the Pozzuoli area (Gulf of Naples). Here the change in level is caused by volumetric variation in a magmatic core lying 2-3km beneath the surface and which, over time, has given rise alternately to moments of subsidence (as in the partial submergence of Roman buildings such as the Serapide Temple) and moments of uplift. Recently, after a long period of stability, there have been intensive changes in ground level in the Pozzuoli area which have caused not only damage, but also, because of the possible risk of further changes in the magmatic core, have induced thousands of inhabitants to evacuate the area.

3. Exogenic processes (Fig.12.8)

3.1. *Climatic variation and variability*

The variety of climate in Italy has already been mentioned: temperate climates (Köppen's C and D) and nival types (E) are dominant, but there are also some areas of semi-arid climate. For example, in the plains to the north of Cagliari (Sardinia), where the average temperature is 18°C, rainfall amounts to less than 200mm. This range of climate depends on the fact that, while Italy is situated in middle latitudes and therefore generally subject to cyclonic air-flow from the Atlantic, its latitudinal spread means that it is also affected at times by air masses from Africa and continental Europe. The nearly 5000m range in altitude also contributes to the variation and to the marked seasonal

Fig.12.8 Map showing the distribution of the principal exogenic hazards in Italy. 1: areas liable to severe soil erosion and mass movement; 2: areas liable to flooding; 3: coastal aggradation and silting of coastal valleys; 4: coastal erosion

differences experienced in many areas. The classical Mediterranean climate (Köppen's Cs type) is only to be found along the coasts and inland as far as the first main hills. Over most of the country, average annual temperatures are over 12°C, but reach 20°C in parts of the south, Sardinia and Sicily, while falling as low as -18°C in the highest parts of the Alps. The number of days with frost exceeds 100 only in the Alps and in a few scattered parts of the Apennines, particularly in Abruzzi and the Calabrian hinterland.

Mean annual rainfall likewise shows great variation from one part of the country to another. The existence of semi-arid areas with only a few hundred millimetres has already been mentioned: parts of Sardinia, Sicily and Puglia fall in this category, but also a large part of the Po plain. The latter, home to Italy's most important agricultural and industrial areas, has a modest rainfall which is, however, compensated by two factors - the dense river network and the generally low level of evaporation especially in winter. In the coastal regions on the other hand, there is greater evaporation accompanied by rainfall amounts no higher than 800mm. In complete contrast, precipitation over the whole of the Alps and Apennines is over 1000mm; many areas have 2000-3000mm and in the eastern Alps and the Apuane Alps (Tuscany) it reaches approximately 4000mm.

The single most important aspect of precipitation as regards geomorphological processes is its irregularity. The timing of the precipitation varies greatly across the country. In the Alps, most precipitation falls in summer; in the inland areas of the Po-Venetian plains there are two peaks, spring and summer, with a seasonal shift from west to east; in the Apennines there are again two peaks but the autumn one is greater; and along the coasts, rainfall is concentrated in the winter, with long periods of drought in the summer. Superimposed on this seasonal distribution are the irregular extreme events of intense and concentrated precipitation that are crucial to understanding the problems of flooding and erosion.

Temporal climatic variations can of course be traced back as far as the Quaternary. In ancient times as well as more recent centuries, records show significant changes, as in the Little Ice Age. As regards the present century, the monitoring of about 400 Italian glaciers carried out by the Italian Glaciology Committee has provided excellent information on climatic change.

This brief outline will have served to show that not only is Italy characterised by exceptionally dynamic crustal conditions but also by a great variety of climatic conditions both spatially and temporally. It is against this background that a range of geomorphological hazards, the dangers from which are often compounded by human activity over the centuries, must be viewed.

3.2. *The historical evolution of land use in Italy*

Since prehistoric times, human activity has been modifying natural ecosystems and altering the landscape. The appearance of agriculture involved deforestation, and from this time, accelerated soil erosion became an ever-growing environmental problem. Generally speaking, the longer an area has been the scene of human activity, primarily agriculture, the more it will show signs of the degradation to which it has been subjected over the centuries.

All Mediterranean countries, the seats of ancient civilisations, show traces of a long agricultural past in their extremely articulated landscapes fashioned in often poorly cemented substrata. The soils of these regions, and particularly Italy, have not only been exposed to harsh climatic conditions but to long-term utilisation, which has not always adopted the methods and techniques of conservation.

In the early stages, negative effects were not so much linked to primitive cultivation techniques, involving only human or animal power, but to the extensive deforestation which was the precursor. After the first stages, cultivation was extended as far as the local morphological conditions (mainly slope angle) and the use of animal power would permit, or as far as the soil was known to be productive, and an acceptable balance was often achieved between human activity and the natural environment. Settlements were few and far between, but well distributed over the land, following certain basic and simple criteria to guard against natural hazards such as slope instability or flooding.

In Italy, this situation prevailed practically until the Second World War and then came to an abrupt halt with the massive industrialisation of the last 40 years. Since the 1950s, there has been mass abandonment of farmland, especially of the least favourable areas which, unattended, suffered from degradation (Rodolfi, 1986).

Since then, there has been expansion of towns and industrial areas which, together with the necessary infrastructure of communication links and social amenities, has taken place preferentially on valley floors, despite the fact that simple geomorphological assumptions showed many of these areas to be at risk from flooding. Sections of river beds were artificially modified, either by making them narrower to accommodate more buildings, or by making them deeper in the process of extracting building materials for the ever-growing construction industry.

Farming was then forced towards the hills, the so-called "sloping areas", already in a precarious equilibrium and where the land and the substrata have poor geotechnical properties. In addition, to allow complete mechanisation of farming procedures, from ploughing through to harvesting, plots were enlarged, old terraces flattened with bulldozers, and the old and efficient hydraulic networks which had helped to maintain a precarious equilibrium were destroyed (Fig.12.9). This resulted in an immediate increase in the incidence of water erosion and mass movement on the slopes, while the increase in runoff brought about flooding, sometimes catastrophic (Chisci, 1986).

Water consumption for both domestic and industrial use increased sharply, making it necessary to exploit deeper levels of groundwater, with the result that irreversible subsidence started to appear. At the same time, the construction of reservoirs considerably reduced the natural supply of material to beaches, intensifying coastal erosion.

All these phenomena, strongly interconnected in sequences of cause and effect, have involved every main hydrographic basin in Italy; they are still active, though planners are now more sensitive to environmental problems and are attempting to eradicate the causes, or at least to mitigate the effects (CNR, 1982, 1983).

3.3. *Slope processes*

3.3.1. *Water erosion* Under normal climatic conditions, soil erosion is a relatively slow and imperceptible process whose consequences for the soil and the landscape may be distinguished only over a period of time, ten years or more. In certain circumstances, however, this process may be accelerated to the extent that it can produce considerable degradation even during a single meteorological event.

The danger of severe erosion arises when there are several adverse factors at work simultaneously, such as intense and concentrated rainfall (high rainfall erosivity), low

Fig.12.9. Intensive cultivation needs large and level fields: a view of severe soil erosion after heavy rains which followed ploughing (photo: G.Rodolfi).

resistance of the soil and substrata to erosion (high erodibility), steep and long slopes, low density of vegetation (caused by climatic conditions or, more often, by the prevalent form of agricultural use), and lack of, or inappropriate, intervention.

All these factors, with the exception of the first two, are greatly influenced by human activity. Their spatial and temporal variation, or the prevalence of some over others, create very different situations and result in forms of degradation that may be more, or less, extensive and evident (Alexander, 1980; Noe and Rossi Doria, 1979).

These general statements are widely applicable in Italy where the climatic parameters, especially those concerning rainfall amounts, intensities and frequency of high-magnitude events, vary greatly from place to place. Even the lithology of the substrata which directly influences the physical characteristics of the soil is highly variable, and unfortunately, highly erodible lithotypes, such as the Plio-Pleistocene sandy and clayey formations, outcrop over large areas (Mancini, 1978).

Frequently, and particularly in southern Italy, there is not only the problem of geotechnically poor substrata but also the hostility of the climate to agriculture and the consequences of human occupation of the land for thousands of years, with farming being carried out today in much the same way as in the past with no concern for soil conservation.

It is difficult to quantify rates of soil erosion in each of the many environmental situations that result from the interplay of the factors mentioned above, despite considerable research. Table 12.1 reports the unpublished estimates of Torri (personal communication) on soil loss following rainfall classified as "heavy" in some areas of southern Tuscany in September-November 1987.

Table 12.1. Estimated soil losses during single storms in southern Tuscany (courtesy of D.Torri, unpublished data)

Date	Locality	Soil losses, t/ha
September 1987	Impruneta (Florence)	300-400
October 1987	Gallena (Siena)	0-30
	Cotorniano (Siena)	200
	Frosini (Siena)	130
November 1987	Vulci (Siena)	100-300

The estimation of soil loss in these cases has been determined by measuring the depth and width of the rills developed after the event. In each case, the rills had cut into the soil as far as the plough layer (Fig.12.10) and to a maximum width of 4m (at Vulci); farther down towards the valley, where there are abrupt breaks of slope, fans formed with a radius of 4-5m and sometimes even over a metre thick.

For a small-scale survey, however, it is better to select land with morphological features that show evident signs of active degradation over broad areas; or to refer directly to the actual amounts of material delivered to the river system. For this purpose, easily accessible data are provided in the statistics on suspended load of the principal rivers of Italy, published in the Hydrological Annals by the Ministry for Public Works (see Federici, 1980).

The Po, the largest river in Italy, carries in suspension an average of just under 14 million t of material per year right to the end of its course (the Pontelagoscuro recording station). To this figure should be added about 10 million t of dissolved matter. The total load is, because of the size of the Po basin, greater in absolute magnitude than for any other river in Italy, but there are in fact several other rivers that, in proportion to their size, carry relatively more. This is related to the fact that there are other parts of Italy where the pedological, geological and climatic conditions favour soil degradation much more than in northern Italy. For example, the Apennine streams provide more than 75 per cent of the material carried by the Po, whereas the Alpine tributaries are responsible for only 25 per cent.

Compared to the load of the Po, which averages 528kg/s, the Arno carries 65kg/s, the Ombrone 41.5kg/s and a very small stream, the Orcia, which flows through the Neogene clays of southern Tuscany, transports almost 50kg/s of suspended material. Similarly high values can be found among the rivers draining the Adriatic slope of Italy

Fig.12.10. Rill developed during a single storm on southern Tuscany. The plough layer, 30cm thick, has been totally removed. Width at mid-distance is approximately 200cm (photo: D.Torri)

(the Reno, 40kg/s) and even higher values are known in the south: for example, the Bradano in Basilicata transports 84kg/s and the Simeto in Sicily more than 100kg/s. The total load carried annually by all Italian rivers together is estimated to be 700t/km^2. If this figure is compared with worldwide data on land-mass denudation compiled by Fournier, it is clear that the annual loss of Italian soil is greater than the world average.

According to studies made by the Hydrographic Survey of Italian Watercourses at 70 gauging stations, 60 per cent of the erodible soils (covering a total of 141 000km^2) can be classified as highly erodible, 19 per cent as moderately erodible and 21 per cent as subject to a lesser risk of erosion.

Erosion destroys agricultural land first of all, as some interesting data show. The catchment area of the Idice torrent (Emilia) reveals a surface lowering of 4.8mm per year, for example, but values are much higher still for some of the clayey and silty-clay soils in Tuscany. It has become evident that the huge sums of money invested in reclaiming some large areas, apart from any consideration of the prospects of real economic returns in the future, are in danger of being totally wasted.

Large-scale erosion mainly affects the so-called clayey soils, a general term including all the fine-grained fractions (fine sand, silt and clay, in various combinations), which are so widespread as to cover 20 per cent of Italy. Despite the wide variety of forms and degrees of erosion, depending on the lithology of the clays, their structural conditions and, to a lesser extent, on the climatic conditions and presence, if any, of a vegetation cover, there are few regions of Italy that are not characterised by *calanchi*, a form of gully erosion also involving some types of superficial landslide, from the Emilian Sub-Apennines down to those in Abruzzo, in Tuscany, Lazio, Basilicata, Calabria and Sicily, and even in Piedmont (Alexander, 1980; Vittorini, 1977). Wherever well-developed examples of these and other similar forms of erosion (such as *biancane* and *crete* in the Siena area) are found, the landscape appears desolate and uninhabitable. In some cases, there are larger, populated districts (the most famous examples are in the neighbourhood of Siena in Tuscany and Pisticci in Basilicata) that are at serious risk because of erosion which has already destroyed some parts of these centres (Fig.12.11).

Fig.12.11. The town of Pisticci in Basilicata. The town is intermittently being undermined by mass wasting, in an area of generally eroded, "clayey" landscape. The substrata consist of poorly cohesive silty, clayey and sandy deposits of the marine Neogene cycle, subjected to the typical Mediterranean climate (photo: G.Rodolfi).

3.3.2. *Mass movements* The most important form of land degradation in Italy is undoubtedly landsliding. Landslides have occurred frequently in the past, and nowadays have such a strong impact on the economy that the risk of landsliding is regarded as a national threat (Almagia, 1907; Canuti, in press; Canuti and Pranzini, 1988). In addition to their frequency, they vary greatly in extent, type of material involved, mechanism and origin. Whatever type of landslide classification is used, Italian examples of each type can always be found, a fact that is related to the extreme variety of environments together with the range of human activity, as described in the previous section.

Among the triggering factors, the chief ones are related to (a) rainfall (amount, intensity, duration, etc.)(Govi and Sorzana, 1980), which saturates permeable strata and decreases shear resistance, and (b) seismic activity, which affects almost all of Italy.

These gravitational processes affect different-sized areas from a few m^2 to many tens of km^2, and operate at different speeds, from imperceptibly slow creep to catastrophic falls. In the clays which are so prevalent in Italy and which tend to show plastic behaviour, there is usually slow but continuous creep which can be the precursor of rotational slides. Such phenomena often affect areas of cultivation and settlement, threatening farming and the stability of buildings. When there is intense and prolonged rainfall, clay slides can quickly become rapidly-moving mudflows that invade the valleys below.

The more rigid rock strata that comprise most of the Alps and the central ridge of the Apennines are, on the other hand, more subject to planar slides or rock falls. The former develop mostly in stratified formations such as flysch, where different lithotypes alternate, including at least one layer of clay or marl, and where the strata dip at angles equal to or less than the slope angle. Rock falls, on the other hand, occur more often in massive homogeneous formations with a certain degree of fracturing. In both these cases, the movement trigger is not so much due to water infiltration as to other causes - basal undercutting by a river, human intervention or seismic shock.

A survey by the Ministry of Public Works (Rinaldi, 1969) on the incidence of landslides discovered that almost 2000 important landslides occurred in 1957, and 2685 in 1963, a striking increase in this short period. Altogether, an area of 141 235ha was affected in 1963 (Tables 12.2 and 12.3). Since then, several other areas, all across the country, have become unstable, sometimes severely damaging settlements and hindering agriculture. In addition, there are thousands of minor slides and slips which occur everywhere during periods of particularly heavy rain, as happened in November 1991 and 1992. Clearly, the amount of damage caused by these phenomena is immense, especially when one considers that some 1000 built-up areas are at serious risk. These include some centres which, apart from the humanitarian aspect, are of immense artistic value, such as Orvieto and Todi in Umbria. A general review of this aspect has recently been made by Canuti (1992).

The distribution of landslides is influenced, above all, by the rock types and the climate in the various regions. The map (Fig.12.8) indicates that the only zones that are practically untouched by mass movements are Sardinia and Puglia (see also Tables 12.2 and 12.3). The regions that are most affected, on the other hand, are central and northern Sicily, Calabria, Campania, Molise, Abruzzo, Emilia, Trentino and Friuli. The data are thought to under-estimate the true situation. The following paragraphs outline some examples from the report published by Federici (1980).

There have been some rapid landslides of huge size. The volume of rock dislodged during the prehistoric landslide that blocked the river Adda near Bormio is estimated at

Table 12.2. Areas affected by mass movements, 1963, and their regional distribution (Rinaldi, 1969)

Region	areas affected by mass movements (ha)				
	0-50	51-100	101-200	201-1000	1001-2500
Piemonte	88	10	10	4	-
Valle d'Aosta	84	-	-	-	-
Lombardia	102	3	-	3	-
Trentino-Alto Adige	48	1	-	-	-
Veneto	55	4	3	-	1
Friuli-Venezia Giulia	19	1	-	-	-
Liguria	50	1	2	-	-
Emilia Romagna	327	21	10	6	-
Toscana	70	5	3	4	2
Umbria	28	1	1	1	-
Marche	123	24	7	2	-
Lazio	94	2	-	3	2
Abruzzi	153	8	8	10	-
Campania	227	63	12	24	6
Puglia	43	2	-	-	-
Basilicata	133	15	5	5	-
Calabria	216	30	8	9	-
Sicilia	209	96	62	35	1
Sardegna	9	-	-	-	-
Totals:	2078	277	131	106	13

180 million m^3; about 500 million m^3 apparently slithered from the Dolomite group of Antelao at different times, huge landslides that blocked rivers and created broad lakes which can still be seen today. The landslide of unknown date that formed a barrier across the river Sagittario in Abruzzo, giving rise to the beautiful lake known as Scanno; the landslide that occurred around 3000 BP creating Lake Molveno in the Brenta Mountains of the Dolomitic Alps; and the famous landslide which plunged into the River Cordevole (Belluno Alps) in 1771 creating Lake Alleghe, may also be mentioned. In addition, there are countless small lakes that are known to have originated in this way, particularly in the Apennines, but their brief life-span is equally well known.

A conspicuous phenomenon in the Alps was that of the post-glacial collapse rockfalls (*marocche*): these probably resulted from the withdrawal of valley-side support during deglaciation in the late Quaternary. Some valleys, such as the Brenta, were partially blocked in this way.

Table 12.3. Number of mass movements, number of built-up areas at risk and percentage of those that are at risk, for each region of Italy (Rinaldi, 1969)

Region	Number of mass movements	Number of built-up areas at risk	Per cent of built-up areas at risk
Piemonte	112	37	3.35
Valle d'Aosta	84	32	2.93
Lombardia	108	20	1.84
Trentino-Alto Adige	49	5	0.46
Veneto	63	36	3.25
Friuli-Venezia Giulia	20	8	0.74
Liguria	117	31	2.90
Emilia Romagna	364	88	8.00
Toscana	100	54	4.90
Umbria	31	20	1.84
Marche	146	66	6.05
Lazio	101	53	4.80
Abruzzi	179	107	9.80
Campania	332	175	16.00
Puglia	45	24	2.30
Basilicata	158	104	9.50
Calabria	263	75	6.85
Sicilia	403	151	13.75
Sardegna	10	8	0.74
Totals:	2685	1094	100.00

The human consequences of the larger landslides, some of which were probably triggered by earthquakes, can only be described as catastrophic. In 1618, the village of Piuro in the Chiavenna valley of Lombardy was completely destroyed by a huge landslide; the same fate befell Antronapiana in the Ossola valley (Piedmont) in 1642. Other examples are Montepiano (Abruzzi) in 1765, Montemurro (Basilicata) in 1857, Campomaggiore (Basilicata) in 1884, and so on, a continual sequence of disaster and mourning (600 victims in Montepiano alone), right up to the most serious landslide of modern times at Vajont. The devastation of the Piave valley and the 2000 victims who were drowned were the consequences of the colossal wave that swept out of the Vajont reservoir and down the narrow gorge below it, on the night of 9-10 October 1963. The wave itself was caused by the collapse of 250-300 million m^3 of rock from the entire flank of Mount Toc (Selli *et al.*, 1964); this gigantic landslide in turn was the result of constructing the reservoir in an unsuitable location such that the raised water level and altered porewater pressures led to failure of an already unstable slope (Hendron and Patton, 1985).

In December 1982, an enormous mass movement (220ha) involved part of a slope on the northern outskirts of Ancona (Marche), facing the Adriatic Sea (DSDT, 1986). The slide affected 3661 inhabitants and 280 buildings, including the city hospital; 865 homes were either damaged or ruined. Serious damage was done, at the toe of the landslide near the coast, to the railway, to the Flaminia road (which was lifted 4-5m from its original level) and to the city's network of water and gas pipelines. Research has shown that this area was subjected to mass movement in the past.

In July 1987, after an abrupt rise in temperature above zero, accompanied by intense rainfall, rapid thawing of mountain snow in Valtellina, besides causing flooding of the River Adda and its tributaries, also brought about an enormous landslide which blocked the valley at a point not far from the site of the prehistoric landslide near Bormio mentioned above (Laffi and Fossati, 1988). The slide, which buried the town of S.Antonio, caused 20 deaths and created a lake which, since it was extremely dangerous for the densely populated valley below, was gradually drained artificially, with considerable risk for those involved in the work (Fig.12.12).

This repetition of the same phenomenon in adjacent areas, perhaps even with similar structural and geomorphological features, calls for thought regarding the lessons that can be learnt from past events, and from the existence of palaeo-landslides, ready to be reactivated by human error. Research in this field can prove of the highest value in establishing the degree of risk in adjacent areas, and in attempting to prevent future tragedies or to mitigate the risk.

The presence of palaeo-landslides is already an indication of those areas where there is a risk of renewed movement. If the previous events can be dated, then it is possible to establish the frequency of the phenomenon and to relate it to the environmental conditions - and, occasionally, to the historical and social situation in the area in question. In this way it may be possible to foresee, even if only approximately, the evolution and trend of the slope instability phenomena, and tragedies such as the Vajont disaster need not be repeated.

3.3.3. *Avalanches and ice falls* Although they are a feature only of mountainous areas with relatively few people compared with the lowlands, snow avalanches (Capello, 1985; Negro and Simonetta, 1986) are a sudden geomorphological hazard and claim many victims every year. The risk is highest in the Alps but is also present in the Apennines. As time goes by, the number of victims is steadily rising because of the great increase in winter sports and tourism in mountain resorts. These visitors are usually not aware of the risks despite the fact that the Avalanche Unit constantly issues warning bulletins when conditions are unsafe.

When an increase of temperature follows heavy snowfall, snow masses of any size can be dislodged from an Alpine or Apennine slope; the principal damage results from impact and airblast, and deaths from burial. There are places where records show that avalanches have been falling regularly since ancient times. These places are easy

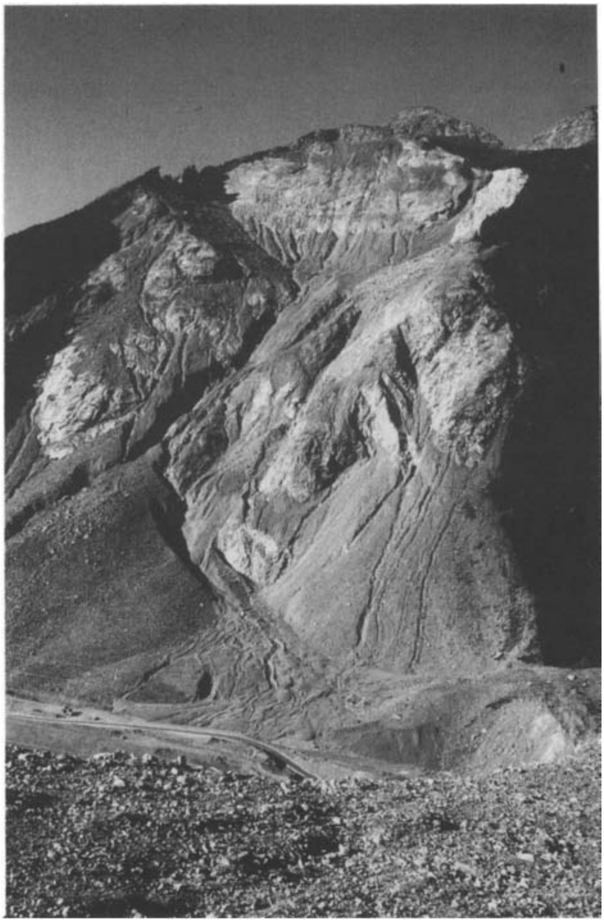

Fig.12.12. The scar of the huge landslide that dammed the River Adda in 1987. Some secondary falls are still active in the upper part (photo: G.Rodolfi).

to avoid because unmistakeable signs, especially avalanche chutes, are visible in the landscape. Historic towns are usually sited in locations carefully selected to be off the tracks of recurrent avalanches, but new tourist resorts have often sprung up in less suitable sites. Thus the situation arises that, because of crowding and ignorance, avalanches occur in areas considered "safe", very often with disastrous consequences.

A much more limited hazard is represented by ice falls from glaciers in the Alps. A recent example was the collapse of part of the Coolidge glacier in the Monviso Group (Dutto and Mortara, 1992).

3.4. *Fluvial processes*

3.4.1. *Vertical and lateral river erosion* The dynamics of slopes are closely interlinked with those of rivers; in fact, many mass movements start because of the activities of rivers at the toe of the slope. Fluvial activity varies over time because of meteorological events, climatic change and tectonic uplift or subsidence. Apart from the first of these, such changes are usually slow and long-term. In Italy, however, because of the highly erodible soils and sub-strata prevailing over extensive areas, rapid transformation of the landscape can take place during just a few major events, or even during a single one.

Reference to a small-scale relief map of Italy and its drainage pattern shows that the more "continental" part is drained by the Po, which collects water from the southern slopes of the Alps and the northern slopes of the Apennines. In the peninsula section of Italy, the drainage situation depends primarily on the Apennine structure. On the Adriatic side, those rivers which are not tributaries of the Po are usually short and run perpendicular to the main tectonic structures, particularly in the Marche-Abruzzi stretch. On the Tyrrhenian side, the rivers tend to be longer since in their upper parts they run through several intra-Apenninic tectonic depressions whose axes are parallel to the main chain; once they have left these basins they turn to flow normal to the coast, making their way through wide alluvial plains (Travaglini, 1980).

The situation in the more southerly parts of the chain is somewhat different again. This section is more tectonically active: Quaternary uplift, as part of the broader pattern of neotectonic activity, is still going on relatively rapidly over most of Calabria and part of Basilicata, but is also a feature of parts of the Apennines farther north. Pliocene sediments in Tuscany have been subsequently uplifted by 900m, and Pleistocene sediments in Calabria by a similar amount. The average uplift for the Quaternary is of the order of 1mm/year, though the movements have not been continuous.

Another factor which has encouraged rapid change in the river system is that, in most cases, rivers in the Apennines flowing across coherent rock types, such as arenaceous flysch, meet less resistant lithologies at the foothills where valleys can be rapidly incised. This tendency has been reinforced by human activity, especially gravel extraction from the river beds. For example, renewed erosion has begun in the Apenninic foothills around the right-bank tributaries of the Po and among the Adriatic rivers. The consequent lowering of the river beds by a few metres has led to the undermining of the piers of several bridges. Table 12.4 gives some examples of this (Tazioli, 1982). In the lower stretches of rivers that flow across alluvial plains, or in intermontane basins, especially in meandering reaches without bank protection, lateral erosion is a problem linked to this lowering of river beds (Fig.12.13).

3.4.2. *Flooding* Excessive deposition of material in river beds can occur when large amounts of material are being supplied to the river by intensive slope degradation (cf. section 3.3). The only time when this material can be evacuated is during floods; as soon as the discharge decreases, the load is deposited and is spread out across the whole width of the channel. This behaviour is typical of many Italian rivers, especially those in

Table 12.4. Data on river-bed lowering of some Italian rivers. The most damaging results are the undermining of bridge piers, increase in the depth of the water table, and reduction of solid load in transit to coastal beaches; some water-supply conduits are also left hanging, and flooding downstream may increase.

Region	Rivers	River-bed lowering	Causes
Piemonte	Alpine and Apenninic	2-6m	Gravel extraction; hydraulic construction works
Veneto	In floodplain areas	2-6m	Gravel extraction; dams and weirs
Emilia	Tributaries of the River Po	2-12m	Gravel extraction; channel narrowing; re-afforestation
Toscana	Arno and Magra	irregular	Gravel extraction
Marche	On the Adriatic slopes	1-8m	Gravel extraction
Basilicata	On Ionian slopes	20-25m in 200 years	Geological and climatic; gravel extraction; dams
Calabria	Tributaries of the Crati river	variable	Flooding

the south - known as *fiumare* (Fig.12.14) - which are characterised by episodic discharge, periods of flooding when there are strong currents and heavy loads alternating with periods when the channel becomes virtually dry and the debris is deposited. In the case of channels which are artificially embanked, along the Po for example, sediment deposition is restricted to the channel.

The effect of this process of aggradation is a progressive rise in the level of the river bed which, when embanked, can become higher than the land around. These so-called "hanging" river beds present serious dangers during flood discharge, breaching of the dykes leading to inundation of the surrounding areas, as occurred recently (December 1990) for the rivers of south-east Calabria draining to the Ionian Sea.

A report by Federici (1980) presents data on floods in Italy and describes two particular events. There have been some truly exceptional floods causing terrible damage. In March 1935, for example, an intense flood inundated the Velino-Nera basin in Lazio,

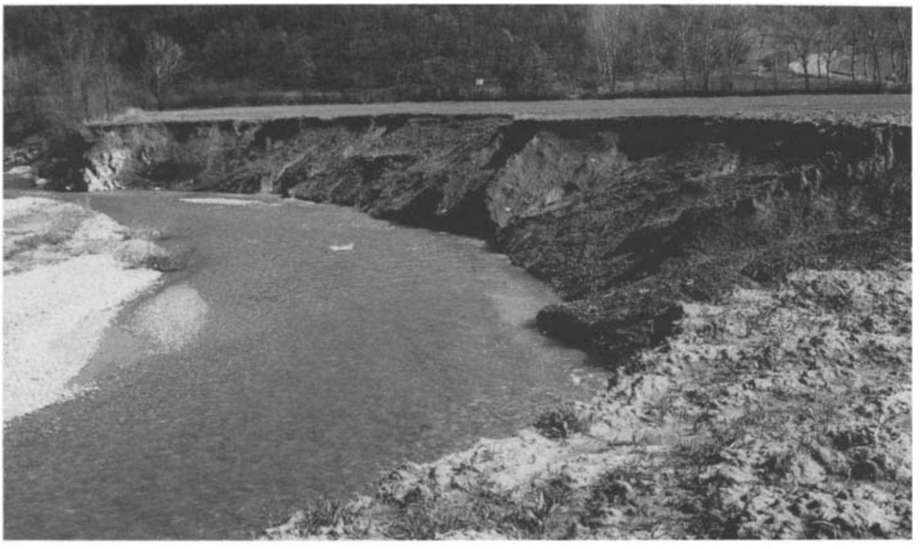

Fig.12.13. (*upper*): Riverbanks cut in alluvial materials of intermontane basins are rapidly undermined if not protected (photo: G.Rodolfi)
Fig.12.14. (*lower*): A typical *fiumara* along the Calabrian coast. This intermittent river, coming from the Sila massif, deposits its bedload to form an extensive alluvial fan. Settlements along the Ionian coast, 300m farther downvalley, are at a high risk from floods (photo: G.Rodolfi)

the Liri basin in Campania, part of Basilicata, as well as Puglia and Calabria, affecting a total of 50 000km^2. In November 1951, the Polesine region (Po delta) between the Po and Adige rivers was inundated by 3000 million m^3 of water, causing inestimable damage to crops, cattle, public buildings and, worst of all, about 100 deaths (Gambi, 1953). The same year saw serious floods in Sardinia, Sicily, Calabria and Val Padana (Fabiani, 1952). In November 1966, many parts of Italy were struck by terrible flooding which was particularly violent in Trentino, Venetia and Tuscany, creating havoc in Florence. Again, more than 100 lives were lost and the consequences of the material damage were felt for many years. The whole world became aware of the threat to Italy's cultural heritage.

Although these dramatic events received international public attention, it should be remembered that many others, smaller and less striking, have affected Italy. At present, flooding is one of the most common and dreaded calamities in the country.

Mapping of the extent of flooding for the period 1946-76 shows that the phenomenon is so widespread that it leaves practically no region untouched. One of the areas most affected is north-eastern Italy, where immense areas including the Po delta and the lower basins of the Bacchiglione and the Brenta are periodically submerged. Flooding is also a frequent occurrence in the middle and upper basins of the Adige and Piave; all river basins in Piedmont, especially in their middle reaches, near the points where they enter flat land, have also been hit by flooding. Some floods in Emilia-Romagna have been destructive but do not rank so high on the national disaster scale. On the other hand, the Arno, Ombrone and Tiber basins in Tuscany and Lazio have on occasion been the scenes of some colossal floods, causing havoc to land and property and many deaths (Losacco, 1967). One can also bring to mind the overflowing of the lower courses of the Abruzzi rivers, and of the rivers Ofanto and Carvaro in northern Puglia. Other flood-hazard zones include the lower courses of the Calabrian rivers and the lower part of the Liri. The islands are also affected, especially Sicily, with serious damage on occasion to the areas in and around Catania, together with all the major southern and eastern basins, especially in the Trapani district. The areas most liable to flooding in Sardinia are the provinces of Sassari, Cagliari and the lower reaches of the River Flumendosa.

Some of these events can undoubtedly be considered exceptional, as far as the extent and intensity of flooding are concerned; but an interesting survey (Caloiero and Mercuri, 1980) shows that in the period 1921-70, all of the Italian regions were affected either individually or in groups by destructive flooding that had serious consequences. For example, there were 11 calamities in Piedmont of which 4 were extensive and violent; 30 in Liguria, where 10 were particularly serious; 29 in Tuscany (5 serious); 17 in Umbria and Lazio (5 serious) and more than 14 in Sicily (4 serious). Altogether, 266 floods were recorded, 67 of which were particularly large, intense and destructive. Only 7 years in this 46-year survey passed without large-scale flooding. Flooding is liable to occur in any month from November to June but the most likely period is the autumn, especially November: there is in each region a clear relationship with the rainfall régime.

During November of both 1991 and 1992, several areas in Liguria and more particularly in Tuscany were again subjected to severe floods, as a consequence not only of heavy rains but also of improper land management.

3.5. *Coastal erosion*

Extending for more than 8000km, the coast is an important economic and social asset, especially in respect of recreation and tourism (Pranzini, 1985; Zunica, 1987). It also presents certain hazards to its use and development, notably the problems of coastal erosion and recession.

While it would be unrealistic to expect a balance between sedimentation and coastal erosion for more than short periods, it is unfortunately quite clear that the present-day dynamics of the Italian coastline are tipped towards erosion (Caputo *et al.*, 1991) (Table 12.5). It is also evident that coasts characterised by high cliffs, as in Liguria, parts of Marche, Campania, parts of Sicily and Sardinia, Calabria and parts of Puglia, have preserved their basic forms over long periods of time, the only exceptions being some parts of Liguria and Campania where urbanisation has required preventive measures against recurrent landslides. Some heavily used coastal roads, as in western Liguria, around the Sorrento peninsula (Campania) and in Calabria have been particularly affected by this hazard.

The low coasts, however, are the ones which suffer the most from erosion (Fig.12.8), and the present global rise of sea level is undoubtedly exacerbating this problem. The first signs of serious coastal recession appeared in the second half of the nineteenth century, but up to 1950 only certain areas (such as the Tuscan coast, parts of which have receded 1km during the last 100 years) have required artificial defence works. Since the 1950s, coastal erosion has increased dramatically, and many resorts have suffered economically because of their receding beaches. A good example is the Emilia-Romagna coast (Adriatic) which is internationally famous for tourism and is visited by 5 million people a year; of its 100km of beaches, one-third are undergoing severe erosion and another third have needed artificial protection. The rest appear to be stable, though in a precarious state. Some other Adriatic coasts are in a similar situation, if not worse.

Some interesting historical conclusions can be drawn from archaeological research which has permitted changes in the Ionian coastline to be reconstructed throughout the centuries. From 1954 to the present, there has been general recession of the coastline, less in the north but greater in the south, where it is as much as 6m per year. In the case of the Tyrrhenian coastline, there is recession almost everywhere, even where small sandy bays are protected between two headlands, as along the Calabrian coast. In the longer sandy stretches of Campania, Lazio and Tuscany, including the National Parks of Circeo and San Rossore, erosion is evident. In many cases, encroachment by the sea is witnessed by the progressive destruction of the dune barriers which still border many coastal areas of the peninsula and the islands.

Elsewhere, indications are given by the disappearance of deltas, for example of the Arno, the Ombrone and the Tiber, which for centuries used to project into the sea. It has also become necessary to defend many built-up areas, such as Ostia, Fiumicino and others. Work on the coasts has been massive and has often altered the original appearance (Fig.12.15), though many natural beauty spots remain.

Table 12.5. Changes on the Italian coasts. *Source*: Atlante delle Spiagge Italiane (*Società Italiana Elaborazione Cartografiche*, 1984).

Region	a	b	c	d	e	f
Liguria	60.5*	44.0	16.5	0.5	4.0	12.0
Toscana**	440.0	220.5	219.5	35.5	93.5	90.5
Lazio	287.5	63.5	224.0	10.0	125.5	88.5
Campania	72.0*	6.0	66.0	-	13.0	53.0
Calabria	271.5*	35.5	236.0	4.5	191.0	40.5
Sicilia	47.5*	5.0	42.5	4.5	6.0	32.0
Basilicata	56.5	18.0	38.5	-	38.5	-
Molise	34.0	-	34.0	-	26.0	8.0
Abruzzo	126.0	14.0	112.0	2.5	57.5	52.0
Marche	170.0	4.5	165.5	6.5	62.5	96.5
Emilia Romagna	150.0	-	150.0	18.5	60.0	71.5
Veneto	156.0	-	156.0	14.0	66.0	76.0
Friuli	100.5	14.0	86.5	-	2.5	84.0
Totals	1972.0	425.0	1547.0	96.5	746.0	704.5

a. Length of coastline investigated (km) [see * below]
b. Length of high coasts
c. Length of low coasts
d. Length of advancing coastline
e. Length of retreating coastline
f. Length of naturally stable or artificially stabilised coastline

* Not all parts of the coastline in these provinces were investigated. The figures refer to those parts that were studied; for comparison, the total lengths of coastline are: Campania 350km, Calabria 686km, Liguria 316km, Sicilia 1030km

** Excluding Elba

It is certainly not easy to propose practical solutions to these problems. Often, the cause of coastal recession may be traced to a reduction in the solid load of the rivers entering the sea, rivers which are often regulated by barrages built to protect against flooding, for the storage of water and for electricity production. But, absurdly, even when there are no dams, the sediment load of the rivers may still be reduced by land reclamation schemes in mountain basins. There is one other specific cause in the last 40 years: the enormous rate of gravel extraction from river beds to supply aggregate for construction of roads and motorways, and the construction industry in towns.

In summary: natural sea-level rise, land sinking in some coastal areas (section 2.3) and, most important of all, the effects of human and economic activity, have combined to make the threat of coastal erosion and recession a serious geomorphological hazard in Italy.

Fig.12.15. The touristic harbour of Cetraro on the Tyrrhenian coast of Calabria (1982). The small harbour is becoming silted, as a consequence of the poorly-advised construction of the jetty, in disregard of the local coastal dynamics (photo: G.Rodolfi)

3.6. *Aeolian processes*

Wind action is perhaps the only geomorphological process which carries no sudden risk in Italy. The incidence of high-velocity winds is in fact low, and the morphological consequences are restricted in area.

Winds capable of causing erosion are the Libeccio (from the south-west) and the Maestrale (from the north-west), affecting the Tyrrhenian coasts; the Bora (from the north-east) and the Tramontana (from the north) on the Adriatic coasts; and the Grecale (from the south-east) and the Scirocco (from the Sahara) on the Ionian coast. Storm-force winds, besides generating high wave energy on the coasts, affect mainly the sandy deposits on beaches, but only for a short distance inland (Fig.12.16). The presence of old vegetated dunes parallel to the coast indicates that aeolian processes were much more active in the past than now, particularly during eustatic falls of sea level in the Quaternary.

Fig.12.16. Sandy deposits along the Sardinian coast; aeolian activity is restricted to the beaches (photo: G.Rodolfi).

Signs of the most active processes today are to be found along the west coast (Is Arenas) and north coast (Golfo dell'Asinara) of Sardinia; along the Tyrrhenian coast near the Circeo headland; and on the coastal plains of Sele (Campania); but nowhere are they a serious hazard. The only place where wind erosion damages agriculture is in the Po delta, in the province of Ferrara, where it is not so much the violence of the winds that is the problem but the physical characteristics of the soil which has developed over loose alluvial deposits of fine sand and silt.

4. Conclusion

Against a background of active tectonics, a varied and changeable climate, the presence of both steep relief and low-lying plains and the extensive distribution of erodible rocks, especially clays, Italy is subject to a wide range of natural hazards that have dominated its history since ancient times. Assessment of the risks to the people must also take into account the population density (a total of 58 million people on 301 000km^2, but locally reaching 190 per km^2), the existence of great artistic and historical monuments, and the highly developed modern economic infrastructure, so that almost every serious event resulting from geomorphological hazards leads to death, injury and great damage to property.

The natural environment and human activity over the centuries are so intertwined that it is not easy to distinguish between what may be blamed on Nature, and what rests on Man. In recent times, the increasing frequency of certain types of disaster and the trends of certain hazards force one to conclude that human actions are at least partly responsible. On the other hand, it is also true that Man has become more aware of environmental problems, and that during the past 15 years especially, much progress has been made in understanding these problems through the work carried out in several national projects by numerous scientists. The following are a few of the relevant projects organised by the National Research Council:

- Maps of the Stability of Italian Territory (1979)
- Volcanic Hazard Maps, with particular reference to Vesuvius (1980)
- Soil Conservation (1982)
- Italian Beach Atlas (1984)
- Italian Catalogue of Earthquakes from the Year 1000 (1984)
- Seismic Reclassification in Italy (1986)
- Neotectonic Map of Italy (1986)
- Structural Model of Italy (1988)

In addition, many other regional investigations have been carried out on flood hazards, the vulnerability of aquifers and on landslide and various erosion hazards.

This great amount of research is still not sufficient to guarantee adequate prevention of disasters; on the other hand, the first benefits of mitigative measures are just appearing, such as were recently seen in the case of the Val Pola landslide (in the Valtellina, Lombardy province: see section 3.3.2), or the most recent earthquake in Sicily. Three groups have now been designated by the National Research Council to carry out specific research tasks: the National Group for Defence against Earthquakes (GNDT), the National Group for Volcano Surveillance (GNV) and the National Group for Defence against Hydro-Geological Catastrophes (GNDCI). The last of these has been sub-divided into three committees responsible for extreme events in river flooding, major landslide hazards and the risk to settlement, and the vulnerability of aquifers.

These groups liaise closely with the Ministry of Civil Protection which was founded, at long last, in 1984. In addition, Basin Authorities have been set up for the nine main hydrographic basins. The National Surveys have also been reconstructed, including the Geological Survey, the Hydrographic Service of the Italian Navy and the Meteorological Service of the Air Force.

In the end, while science can provide better understanding of the causes behind natural calamities, improved civil defence against disasters will only become truly effective when it is realised by all that living in a beautiful and economically prosperous land also carries with it the obligation to live as far as possible in harmony with Nature.

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The following abbreviations are used:
CNEN Comitato Nazionale Energia Nucleare
CNR Consiglio Nazionale delle Ricerche
DSDT Dipartimento di Scienze della Terra
GNDCI Gruppo Nazionale Difesa Catastrofi Idrogeologiche
IRPI-CNR Istituto CNR per la Protezione Idrogeologica
S.EL.CA Società Italiana Elaborazioni Cartografiche

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THE NETHERLANDS

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1. Introduction

Tourist brochures of the Netherlands often show, besides the well-known bulb fields, one or more windmills. When tourists arrive at Schiphol Airport, they may be startled to learn that this international airport lies more than 4m below sea level. They seldom realise the link between this fact and the windmills. In the Netherlands, the 1m contour (Fig.13.1A), separating what are termed the "high" and the "low" Netherlands, marks the boundary of the land that would be inundated if there was no protection by the dykes or the coastal dunes. The low Netherlands represents more than half of the country; the area that lies actually below mean sea level accounts for 27 per cent. On a geological map, the boundary between the so-called high and low parts roughly corresponds to the Pleistocene-Holocene division (Fig.13.1B).

2. The history of coastal flooding and land reclamation

2.1. Holocene evolution

At the beginning of the Holocene, the Netherlands occupied a part of a north-westward dipping, smooth, mostly sandy surface built up by the rivers Rhine (Rijn), Maas and Schelde. During the Saale glaciation, Fennoscandian ice covered the northern half of the Netherlands, depositing glacial and glacifluvial sediments in this part of the country. In the Weichselian glaciation, the Netherlands was a tundra area in which periglacial wind action added coversands and dunes to the surface. In the early Holocene, sea level rose at about 5mm a year, and transgression of the sea amounted to about 100m a year. The coastline retreated eastwards, reaching approximately its present position about 5000 BP. With the rise in sea level, the water table also rose, and peat deposits began to form in swamps and lakes; but where saltwater flooded in, the marine clays and silts of the Calais formation were laid down. At times, a barrier beach formed, subsequently broken by further transgression and replaced by a bar farther inland.

Around 5000 BP, the rate of sea-level rise slowed; a more permanent coastal barrier developed and new bars formed on its seaward side. On top of these bars, low dunes

were built. Behind the bars a lagoon developed. Four zones can thus be recognised:
1. The coastal zone with bars and low dunes, interrupted only by river outlets;
2. A lagoonal zone in which sand, silt and clay resulting from a series of transgressions and regressions were laid down under alternating marine, brackish-water and freshwater conditions;
3. A peri-marine zone influenced by, but never invaded by, the sea. Here the rivers formed levees of heavy clay; between the rivers, peat accumulated.
4. A fluvial zone consisting of levees and basins, formed by meandering rivers.

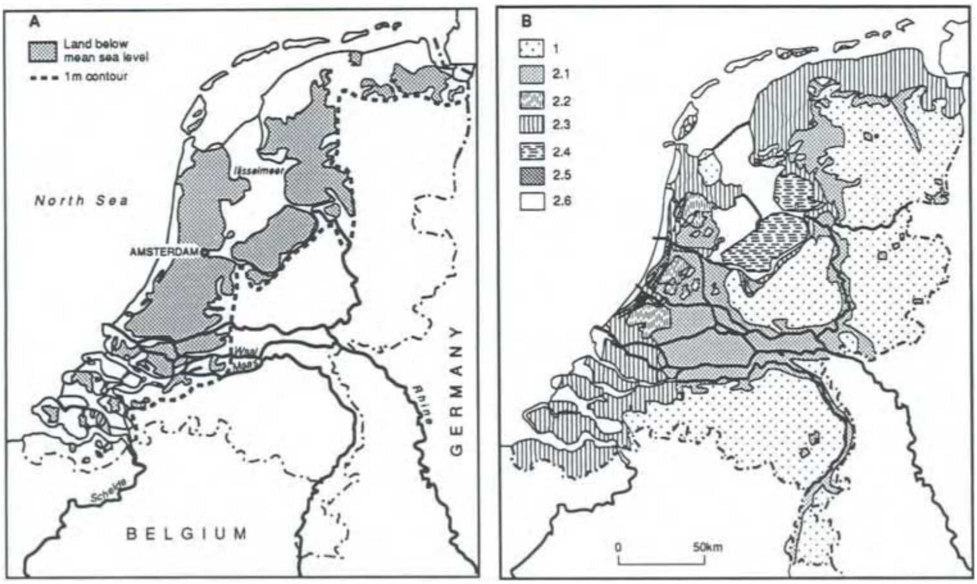


Fig.13.1. A. Land below sea level (shaded) and the +1m contour; B. Geological sketch of the Netherlands. 1 - Pleistocene and older deposits; 2 - Holocene; 2.1 - peat and fluvial sediments; 2.2 - older tidal sediments (Calais formation); 2.3 - younger tidal sediments (Dunkirk formation); 2.4 - lagoonal sediments; 2.5 - old dunes on storm beach; 2.6 - young dunes.

The Calais transgressions ended around 3000 BP and a period of relative stability ensued. For the next 500 years, peat formation was dominant, covering most of the area behind the dunes. Around 2500 BP, there was renewed coastal attack as the Dunkirk transgressions began. New inlets formed, river mouths were widened, peat growth ceased and existing peat areas were eroded. In Roman times (Fig.13.2), the western parts were a marshy tidal area, but still bordered by bars with low dunes.

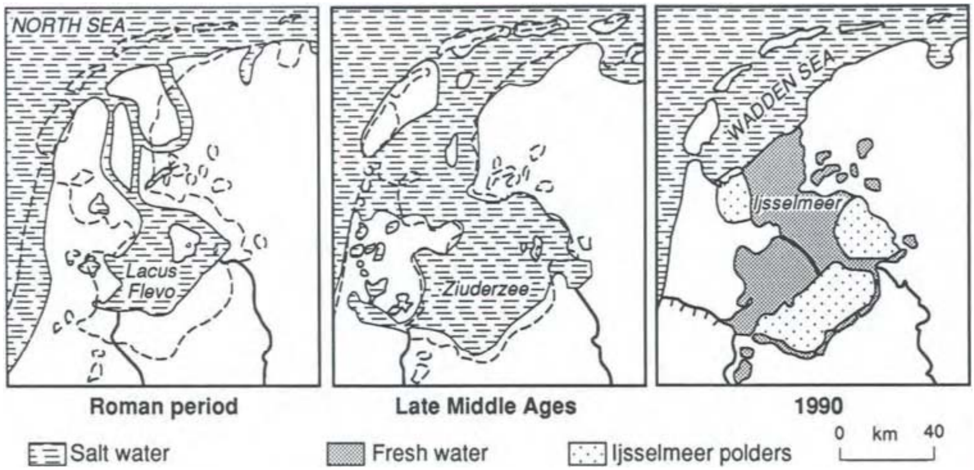


Fig.13.2. The development of the Zuiderzee region since Roman times

2.2. The period of dyke construction and land reclamation

In the early Middle Ages, the barrier coast was heavily attacked by the sea and in the south-west, numerous islands formed. It is thought that the profile of the foreshore steepened, so that more sand became available to form new, higher dunes (up to 20-40m). By now, human influence was becoming significant: people were living on the levees, on the shore and in the peat areas, often on the Pleistocene dunes projecting above the peat. Inland, reclamation of the peat regions began, by the digging of parallel ditches for drainage. As the peat dried, it shrank and the surface was lowered and oxidised. Floods were then able to cause severe damage. By the tenth century, dyke construction along the rivers and coast was already under way, in order to provide protection against flooding. Failures of the earth dykes were frequent and catastrophic: in 1287, during the night of 14 December, it is recorded that 50 000 people drowned in the northern coastal district between the Zuiderzee and the Eems. Other severe floods occurred in 1404 and 1421. During the latter, the Hollandse Waard east of Dordrecht was completely destroyed and transformed into the Biesbos, now a famous wetland.

Coastal attack by the Dunkirk transgressions continued in the later Middle Ages (Fig.13.2). As areas were lost by erosion, especially in the west, attempts were made to reclaim them by dyke construction as soon as sedimentation raised the surface above high-tide level. In this way, polders were formed, which could be drained by opening sluices at low tide. Other polders, mainly farther inland, were formed by reclamation of peat diggings. Peat was dug out, sometimes down to the level of the underlying marine clays, and dried as a source of fuel; groundwater formed lakes in these areas which were later drained by pumping to provide farmland. The floors of such polders are often below sea level, sometimes as low as -6m, and continued to sink as any remaining peat dried out. People began to reclaim the smaller lakes after the Middle Ages, using windmills for pumping (the first wind-driven pump was installed at Alkmaar in 1408), but the larger lakes such as the Haarlemmermeer had to await the advent of steam pumps. The Haarlem lake at this time was a particular hazard for Amsterdam, since during severe storms it tended to enlarge in a north-eastern direction towards the city. It was finally drained in 1852 after 4 years' continuous pumping and later became the site of Schiphol Airport (including the new airport built in the 1960s).

In 1953, a catastrophic storm surge and high spring tide caused a disastrous inundation, resulting in over 1800 deaths. The water set-up by the storm reached 3m above high tide level, and large parts of the islands and the mainland in the south-west were flooded. A contributory factor in this disaster was the fact that the dykes had not been maintained in optimum condition during the German occupation in the Second World War (some islands were intentionally flooded in 1944-45), nor during the economic recession of the 1930s.

The rate of relative sea-level rise has slowed considerably since the Flandrian transgressions, falling to 1-2mm a year in the period 1830-1970. Although most of this consists of eustatic sea-level rise, there is also the factor of tectonic subsidence to be taken into account (see also section 5).

2.3. Twentieth-century engineering works

2.3.1. The Zuiderzee The most important project undertaken in the first half of this century was the enclosure of the Zuiderzee. Such a plan had already been conceived in the seventeenth century but the technical difficulties were then too great. The objectives of the scheme as formulated in more modern times were to protect the areas around the Zuiderzee from flooding, to establish a freshwater basin which could be used to irrigate polders in the northern Netherlands during dry summers as well as for other purposes, and to reclaim new land. In 1916, a flood gave the impetus to design a pilot project which was started in 1927 on the western margin, followed by the formation of the polder Wieringermeer, connected with the island of Wieringen. Closure of the Zuiderzee by a barrier (the Afsluitdijk) was achieved in 1932, and the Zuiderzee then became the IJsselmeer (Fig.13.2). Sluices in the barrier allowed ships to pass through and water levels to be regulated. Over the years, the inflow of the river IJssel and rainfall have transformed the former sea into a freshwater lake. Between 1937 and 1942, the North-East polder (48 000ha, up to 4.5m below sea level) was reclaimed, and a further one, the East Flevoland polder (54 000ha, 5m below sea level) in 1950-57. Finally, between 1959 and 1968, the polder of South Flevoland (43 000ha) was reclaimed. As in the case of the East Flevoland polder, reclamation commenced with the construction of a ring dyke, and a peripheral lake between the polder and the mainland was established. These lakes not only served for collection of surplus water from the polders but also to protect groundwater levels in the mainland area. They now function also as navigation channels and recreational areas.

In 1975, a dyke was built from Lelystad in East Flevoland to Enkhuizen on the western shore of Lake IJssel, with the aim of enclosing a new polder in the south-west named the Markerwaard; in 1991, however, this work was stopped by the Government for ecological reasons.

2.3.2. The Delta Works In 1941, Dr J.van Veen of the Rijks Waterstaat first put forward a plan for the closure of the Dutch estuaries south of the Rotterdam Waterway, with the exception of the Schelde (Fig.13.3).

The Delta Plan project was commenced in 1950 with the building of a 1.5km dam across the Brielse Maas south of Europoort; two years later, the Braakman creek on the south side of the Western Schelde was closed. The disastrous storm surge of 1953 caused considerable damage to the dykes as well as extensive flooding (Fig.13.3B), but by the end of 1953 repairs had been completed and the water pumped out. The event served to accelerate serious discussion about the possibility of closing all the estuaries except the Western Schelde. This would have many advantages, notably

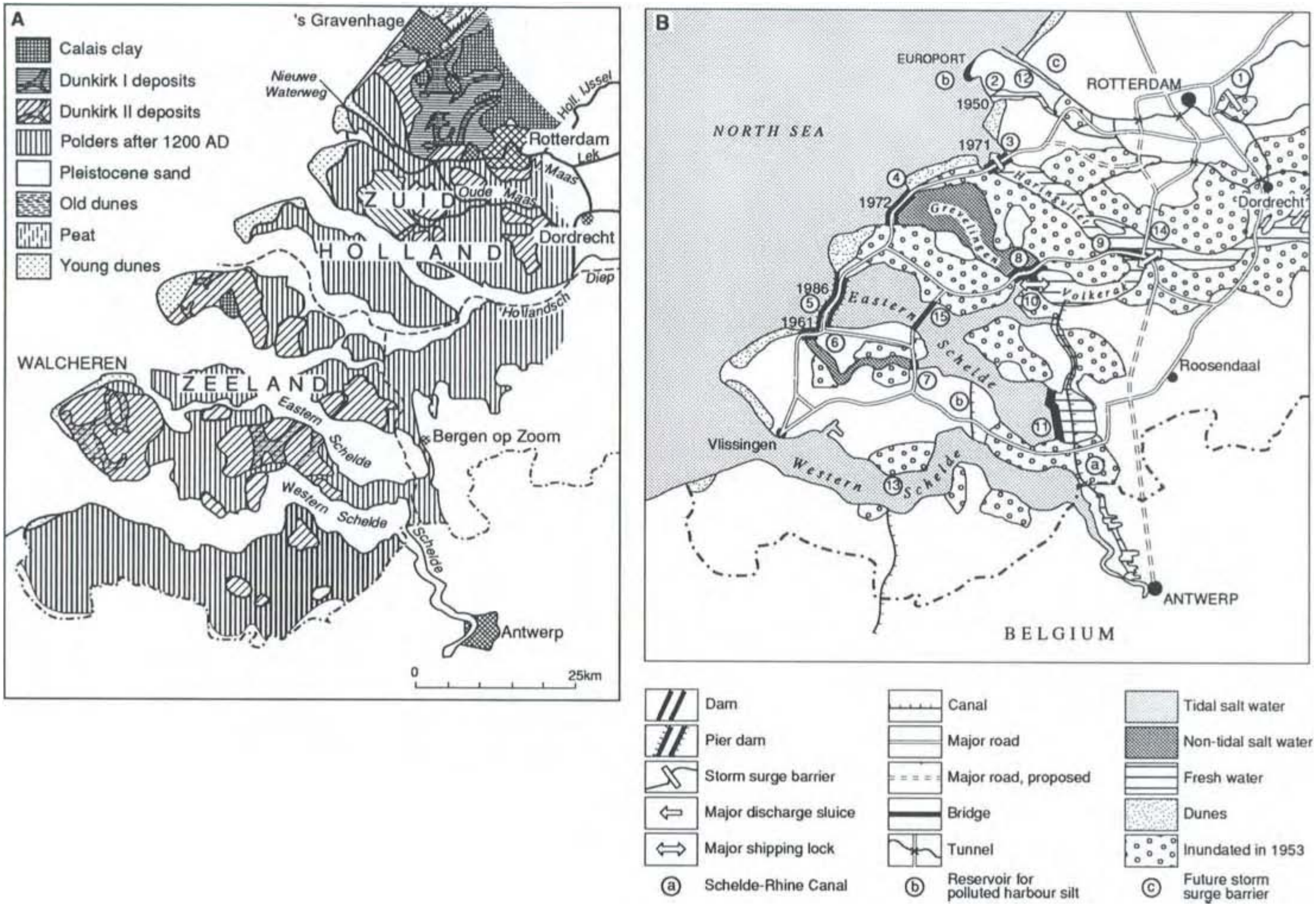
1. a coastline shortened by 700km, and thus easier to defend
2. other existing seawalls could provide a second line of defence
3. creation of large freshwater reservoirs
4. decrease in salt content of the soils of the islands
5. formation and reclamation of some new land.

Confidence to go ahead with this ambitious and highly complex scheme was strengthened by the success of the Zuiderzee and Brielse dams in resisting the 1953 flood disaster.

The Delta Act was passed by Parliament in 1958, but before this, some work had already commenced. The first step was to build the Hollandse IJssel storm surge barrier (1 on Fig. 13.3B) to protect the densely populated and low-lying area of the province of Zuid Holland, which only just escaped flooding in 1953. In 1959-60, a dam was built between North and South Beveland (7), followed by the Veerse Gat (6) on the North Sea coast in the following year.

In 1957, work had already begun to close the Haringvliet (3), the main outlet for the water of the Rhine-Maas system; a barrier with large sluices, of which there are seventeen, was therefore necessary. This was an immense engineering project much of which had to be undertaken below sea level and involving the creation of an artificial island. It took until 1971, when the final closure was achieved by means of dropping huge concrete blocks from an overhead cableway. A similar technique was used to close the 6km Grevelingen dam (8) in 1965, to protect the inner part of the delta area. This had to be completed before the Grevelingen itself and the Eastern Schelde could be closed at their seaward ends.

The Volkerak (9) also had to be closed since, in severe winters, the Haringvliet sluices have to be left open during both low and high tide to let floating ice out: this would then allow salt water to penetrate the Volkerak. The dam here was started in 1957 and took 8 years to complete. Its construction involved agreement with Belgium, since the Volkerak is part of the Schelde-Rhine international waterway (a on Fig.13.3B);


A
Calais clay
Dunkirk I deposits
Dunkirk II deposits
Polders after 1200 AD
Pleistocene sand
Old dunes
Peat
Young dunes
's Gravenhage
Nieuwe Waterweg
Holl. IJssel
Rotterdam
Lek
N. Maas
Oude Maas
ZUID
HOLLAND
Dordrecht
Diep
Hollandsch
WALCHEREN
ZEELAND
Eastern Schelde
Bergen op Zoom
Western Schelde
Schelde
Antwerp
0
25km
B
EUROPORT
1950
1971
1972
1986
1961
NORTH SEA
ROTTERDAM
Haringvliet
Grevelingen
Volkerak
Dordrecht
Eastern Schelde
Roosendaal
Vlissingen
Western Schelde
ANTWERP
BELGIUM
Dam
Pier dam
Storm surge barrier
Major discharge sluice
Major shipping lock
(a) Schelde-Rhine Canal
Canal
Major road
Major road, proposed
Bridge
Tunnel
(b) Reservoir for polluted harbour silt
Tidal salt water
Non-tidal salt water
Fresh water
Dunes
Inundated in 1953
(c) Future storm surge barrier

today, this canal is free of tidal influence. The Volkerak dam also provides an important road link. Sluices near Willemstad allow passage of ships.

Meanwhile, work was also started on closing the entrance to Grevelingen by building the 6.5km Brouwers dam (4); this was completed in 1971.

The largest dam in the complex, that needed to close the Eastern Schelde (5) was commenced in 1967. Although planned for completion in 1978, work was stopped after 5km had been built because of ecological opposition. Oyster and mussel-bed cultivators wanted to keep an open connection to the North Sea, and were also supported by many conservationists concerned with the extensive tidal mudflats, the home of many rare plants, bird colonies and fish specific to this estuary which were under threat from the dam construction. After detailed discussions, the decision was reached to go ahead with the dam but to keep the Eastern Schelde as a body of salt water. To achieve this, gates in the dam are normally left open but can be closed during periods of high storm-surge risk. This decision, however, now meant that further engineering works were needed to separate the salt water in the Eastern Schelde from the fresh water in the Haringvliet, Volkerak and other areas. To do this, so-called "compartmentalisation" dams were required, namely the Philips dam (10) and the Oesterdam (11), which were completed in 1986. By means of a complex system of locks and the design of the dams, navigational needs are catered for, and there is effective separation of tidal saltwater (Eastern Schelde), non-tidal saltwater (in Grevelingen; see below) and freshwater (Haringvliet, Volkerak, etc.). The separation locks work on the principle that saltwater is denser than freshwater; water is supplied or discharged from openings in the lock floors (saltwater) or walls (freshwater) from secondary reservoirs and pumps.

The Oesterdam (11), 11km long, was also needed to separate the Schelde-Rhine waterway from tidal changes in the Eastern Schelde. Related to its construction is a further dyke to the east, the Markiezaat dyke, to protect shipping from strong transverse currents which might otherwise have been a problem in the broad Markiezaat lake.

The storm surge barrier at the entrance to the Eastern Schelde (5). After work re-started on this barrier in 1975, its new design comprised 65 concrete piers and 62 movable steel gates. For this huge engineering undertaking, many new techniques were involved. Compaction of the sediments in the foundations, for instance, was carried out from a special vessel, using vibration, and took 3 years. The concrete piers are between 30 and 40m high above the foundations, took 4 years to build, and were moved into position from another special barge. Finally the gates were emplaced and a road viaduct

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Fig.13.3. (*facing page*) The south-western Netherlands. A. The area as it was in 1952, showing Holocene sediments and the extent of reclamation. B. The Delta Plan works (also shown is the extent of the catastrophic 1953 flood). Numbers on the map indicate: 1. The storm surge barrier in the Hollandse IJssel; 2. Brielse dam; 3. Haringvliet dam; 4. Brouwers dam; 5. The storm surge barrier in the Eastern Schelde; 6. Veerse Gat dam; 7. Zandkreek dam; 8. Grevelingen dam; 9. Volkerak dam; 10. Philips dam; 11. Oester dam; 12. New Waterway; 13. Western Schelde; 14. Bridge to Hellegatsplein; 15. Zeeland bridge

constructed along the full length. Work was completed in 1986, providing full flood protection for the delta area. The gates are closed only if water levels are predicted to exceed 3.25m above mean sea level, which presently occurs on average about once a year.

After the decision to keep the Eastern Schelde as a tidal saltwater enclosure had been taken, there was also a change of plan regarding Grevelingen, which was originally planned as a freshwater lake. Several years after it was enclosed by the Brouwersdam (4), sluices were inserted into it so that saltwater can now enter, though it is not tidal. Since polder drainage and rainfall bring freshwater into Grevelingen, the level of salt has to be monitored, and a siphon allows water with too little salt to be evacuated to the Eastern Schelde.

2.3.3. Evaluation of the Delta Project The principal aim of the Delta works, which was to ensure the safety of the south-west Netherlands from flooding, has been achieved, though the design details of the project changed considerably during its execution. Freshwater enclosures are now less extensive, and confined to the Haringvliet, Volkerak and the Schelde-Rhine waterway. Several enclosures now contain either tidal or non-tidal saltwater, whose seepage into adjacent agricultural areas, as for example south of Goeree-Overflakkee, presents a problem. Although originally envisaged in the plan, no further land reclamation took place. Shore and bank erosion problems have appeared in places.

In 1991, five years after the storm-surge barrier in the Eastern Schelde was constructed, the Rijkswaterstaat directie Zeeland published an evaluation of this part of the project. In summary, the concrete piers and foundations of the barrier have proved to be completely stable, even under the worst storm conditions. The dykes have, however, been strengthened. There has been in effect a 30 per cent reduction in the amount of water entering the Eastern Schelde, but because of the compartmentalisation dams, the tidal range has hardly changed (except when the barrier is closed). Both water current velocity and volume of tidal water have been reduced, which has caused some changes to channel bars which have suffered erosion and smoothing, changes which will continue over the next few years. The possibility of artificially supplementing the sand supply to the bars has been studied, as has also the possibility of supplementing the tidal clays of the *schorren*. The latter are areas that were formerly flooded at extreme high-water stages, but which have also diminished in size because of the compartmentalisation works. New *schorren* may be created in the future; unfortunately, sediment supplementation on such a huge scale may be too expensive.

For the people living in the Delta area, there have been many changes, which can only be briefly mentioned here. Transport links have been greatly improved, ending the relative isolation of some communities, shortening journey times and increasing commuting possibilities, e.g. from Rotterdam. The Zeeland bridge (15), 5km long and opened in 1965, is now toll free. Coastal areas became more accessible for recreation. The biggest changes have taken place on the island of Rozenburg south of the Waterway (12), where almost all agriculture and an important nature reserve have disappeared with the building of the new harbours for Rotterdam at Europoort. The Maasvlakte (Fig.13.6), originally just a sand-bar, is now a reclaimed area of over 1300ha surrounding the deep-water harbours, and already there are plans to extend it seawards another 2km. Another major reclamation project is the Waterman Plan to create 4000ha of new land, along 17km of coast to allow expansion of Den Haag. All these reclamation plans affect the coastal process systems, altering sediment transport; to what extent the effects are adverse remains to be seen.

2.3.4. Problems of salt infiltration and freshwater supply There have long been problems of water supply in the Netherlands arising from its physical geography. The only sources of freshwater in areas where the groundwater is brackish are from rivers and precipitation. The Delta works have helped to mitigate some of these problems, notably with the construction of the freshwater enclosures, but there have also been some adverse effects. Penetration of saltwater or brackish water from the tidal and non-tidal enclosures into adjacent agricultural areas has already been mentioned and is a serious danger. The artificial deepening and widening of some channels, such as the Waterway to Rotterdam, have allowed the saltwater wedge associated with high tide to migrate farther upstream. During severe winters prior to 1973, and occasionally since, when the Rhine was frozen, the salt content of water available to Rotterdam has been known to increase to over 300 mg/l. Since then, however, conversion of the Haringvliet to freshwater allowed three reservoirs supplying Rotterdam to be built in the Biesbos. In the southern part of the Delta, freshwater is obtained mainly from dune groundwater, floating above saline water beneath and accumulated over many centuries from precipitation and infiltration. Such supplies of drinking water have to be carefully conserved, avoiding overpumping and salt infiltration. In coastal areas north of the Delta, partially purified river water is now being pumped back to replenish the underground storage in the dunes.

3. Problems of coastal erosion and coastal management

3.1. Coastal erosion and coastal changes

Because of the low-lying situation of the Netherlands and the dangers of flooding, coastal defences and the monitoring of coastal changes are of the highest importance. Since 1843, annual measurements have been made at points every 1000m along the coast. From these data and from historical maps, it is possible to trace the changes to the coastline over the last 350 years in considerable detail. In general, studies show that the coast of the south-western (delta) area has suffered erosion, the coast from Hoek van Holland to Den Helder (the so-called "uninterrupted" coast) has been stable, apart from erosion in the extreme north and south, close to the tidal inlets, while in the Wadden area of the northern Netherlands, there has been mostly coastal retreat. At the ends of the Wadden Sea islands there has been some progradation and the formation of new beaches. Since 1965, monitoring operations have been intensified; the coastal profile (from 800m seaward to 200m inland) is now measured every 250m; additionally, a longer profile (2.5km) is measured every 5 years at 1km intervals along the coast. Fig.13.4A shows present-day erosion rates. The profile data also allow average rates of erosion or sedimentation to be calculated and a "sand-balance" to be drawn up for each section of coastline (Fig.13.4B). This shows that the beach gradient along the uninterrupted coast will become steeper as sand from deeper water is transported to shallower water.

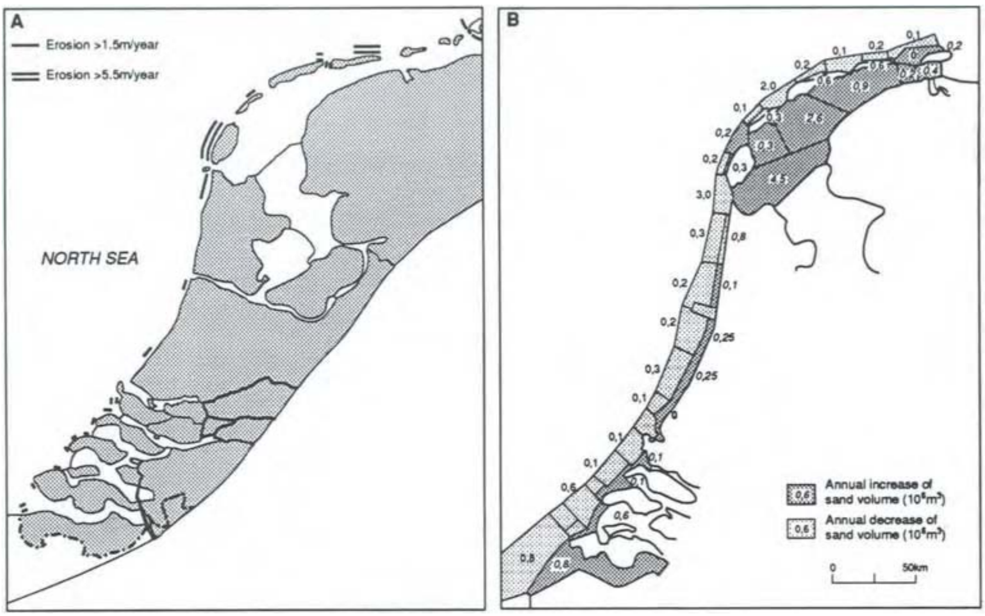

Fig.13.4. A. Erosion rates along the Dutch coast (after Dillingh and Stolk, 1989). B. The sand balance along the Dutch coast (from *Ministry of Transport, Public Works and Water Management*, 1992)

Many coastal changes are explicable in terms of known wave and tide behaviour, but there have also been some puzzling changes whose causes are not fully understood. For example, in the south-west and the north-east Netherlands, the coast sometimes retreats over periods of 40-100 years, followed by an advance over the same length of time. The changes range from tens of metres to several hundred metres, and seem to be connected to the phenomenon of sand waves moving from south to north along the coast (in the Wadden Sea, from west to east), at rates of 30-450 m/year.

In the delta area, offshore channels that formerly connected the tidal inlets are present; their movement towards the coast is one of the main causes of coastal erosion in this region. Another result of the closure of estuaries has been the changing pattern of tidal currents. Offshore sandbars are developing 3-8km from the coastline on the outer edges of the former tidal deltas. It is expected that their formation will be of benefit to Texel, Voorne, Goeree and Schouwen in the next century. Sand is also accumulating in front of the closure dams and a "Voordelta" is growing.

3.2. The dunes

The coastal dune system along the Dutch coast is the largest unbroken chain of dunes in Europe. In width, they vary from hundreds of metres to several kilometres. They are a vital element in the country's coastal defences and prevention of dune erosion is a serious concern. Coastal management of sandy shores began as long ago as the sixteenth century, when the dune foot was protected by timber. Since 1776, groynes have been used; later, marram grass was planted on the dune foot and on the dunes themselves, and sand-drift screens have also been employed. At present, defensive structures such as groynes, rows of piles and dune revetments are used to strengthen about 40 per cent of the dune coast. The dunes are naturally subject to attack from storms and by continuous on-going erosion. Storm damage is not permanent - it is part of a natural process and will repair itself. Much of the eroded dune sand that is transported offshore will be returned to the beach by waves during calmer weather, where it can be picked up by the wind to form new dunes.

3.3. Present coastal management

In 1990, a Government decision was made to maintain the entire coastline more or less in its present position. The various dams and dykes are of course already fixed; on the dune coast, however, some natural movement inherent to a dune area will be allowed, and storm damage producing fresh dune faces cannot be prevented, but measures such as marram-grass planting and erection of sand-drift screens can help to repair damage more quickly.

With many parts of the coast subject to long-term erosion, only part of the sand eroded during storms is returned to the beach, the rest being lost offshore. For some segments where erosion rates are high, where the coast is of high recreational value or where nature reserves need to be protected, artificial beach feeding is undertaken, and since 1990, every year 5-7 million m^3 of sand are in this way added to the beaches. The sand is dredged offshore from depths of at least 20m and then pumped to the beach through a pipeline. The results of a project in 1993 will determine whether this method of beach replenishment is used more widely, or whether other possibilities should be considered: these include the possible construction of barriers orthogonal to the coast, or the creation of large sand dumps at strategic points, from where natural processes could re-distribute the sand.

3.4. The threat posed by relative sea-level rise

At present on the Dutch coast, this amounts to about 20cm per century, but it is possible that this will increase if global warming continues. A Netherlands study (ISOS: Impact of Sea-level rise On Society) on the impact of future sea-level rise has recently been completed, including a worst-case scenario of a 60cm rise in the next 100 years. Though many elements in the predictions are uncertain, it appears that the chief problems will be:

1. A need for increased drainage of water from the polders and Lake IJssel;
2. Increase in the flood hazard along the lower reaches of the rivers; a storm-surge barrier in the Waterway is at present under construction and due for completion in 1996;
3. The safety of some harbours and industrial areas may be threatened;
4. Bridges will need to be raised for shipping;
5. Decrease in the intertidal areas;
6. Various other environmental consequences, especially in the Wadden Sea and the delta areas.

To ensure safety, the coastline will be carefully checked every five years to see if the precautions are still adequate or if they need to be adapted to the changing conditions.

In 1993, the 8th Coastal Zone Symposium was held in New Orleans, USA. Here the Dutch *Rijkswaterstaat* received the first International Coastal Zone Award for its work on coastal and water management in the Netherlands. The Director General in his speech said that "The Netherlands hope to promote cooperation as a key element in meeting challenges for sustainable development of the world's coastal zones".

4. Rivers and the risk of river flooding

4.1. River evolution in the Quaternary

For most of the Pleistocene, the Rhine, Maas and Schelde followed a roughly north-north-westerly course across the Netherlands, including the area that was later to become the Zuiderzee, depositing gravel, sand and clay. In the Saale glaciation, the Scandinavian ice-sheet spread across the northern part of the country as far south as a line approximately from Haarlem to Nijmegen, blocking the northerly courses of the rivers and forcing the Rhine and Maas to flow to the west, partly along channels marginal to the ice. The advancing ice also pushed up ridges of fluvial material and capped them with glacial deposits.

During the subsequent Eemian interglacial and the early Weichselian, the Rhine resumed its northerly course until the middle Weichselian when once again it turned to the west. Around the third century AD, the northern outlet once more came into use.

As well as these dramatic changes in outlet, the river systems have also responded to the various climatic changes by adopting different habits, from meandering to braiding; and the low sea levels of the glacials produced incision, followed by infilling when sea level rose. Around 8000 BP, clay and peat began to accumulate outside the former river valleys. The rapid rise of sea level in the early Flandrian prompted the rivers, fixed by clay banks, to adopt an anastomosing pattern, but by about 5000 BP, the rise had slowed and the rivers began to meander once more; meanwhile, peat accumulation increased. Around 1000 AD, people started to build dykes along the rivers to provide protection against high water and flooding; by about 1400, the dykes were completed.

4.2. The flood hazard on the rivers in former centuries

Formerly, the most dangerous situations in respect of river flooding occurred in winter, when ice jams formed during the break-up of river ice. Behind the ice dams, water levels rose rapidly, and the moving ice floes themselves damaged or destroyed dykes.

The more fundamental and longer-term problem for the Netherlands, however, is the evacuation of excess river water from a land surface that in many parts lies not only below high tides but below mean sea level. Shortly after leaving the German border, the Rhine divides into two branches - the Rhine and the Waal. Near Arnhem, it splits again, the Rhine flowing to the west and the IJssel to the north. Until the 18th century, most of the Rhine water flowed to the Waal, the shortest distance to the coast; the result was that the Waal suffered from floods while the Rhine contained hardly any water in summer. Between 1701 and 1707 the Pannerdens Kanaal (Fig.13.5) was excavated, primarily

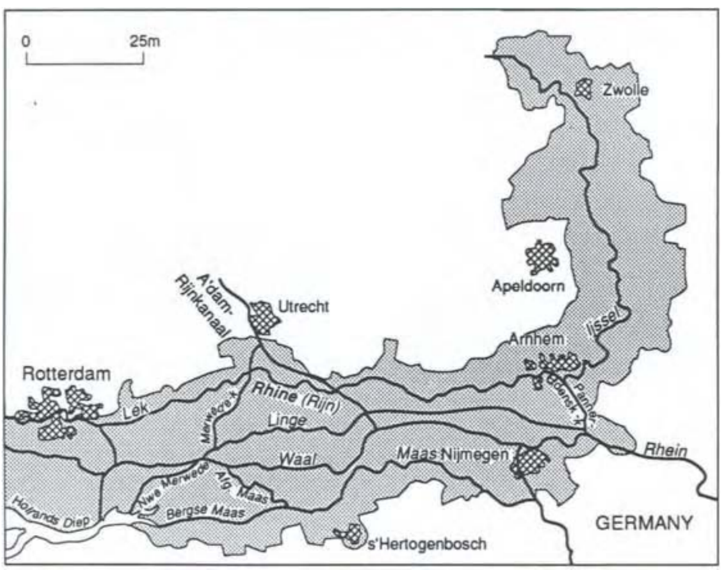

Fig.13.5. The *Rivierengebied* (river area) between the North Sea in the west, the entry of the Rhine into the Netherlands in the east, and Lake IJssel in the north.

for defence but also for water regulation; it directs two-thirds of the water to the Waal and one-third to the Rhine. In 1775, the junction near Arnhem to the IJssel was improved so that one-tenth of the Rhine water entered the IJssel. Until about 1700, the rivers could meander freely, but to control flood water in the Waal and also to aid navigation, regulation works became necessary. To assist the movement of water further, a small river, the Linge, flowing between the Waal and the Rhine, was connected to the Pannerdens Kanaal upstream and the Merwede downstream. In 1870, the Nieuwe Merwede was built to take water from the Waal to the Hollands Diep, and in 1904 the Bergse Maas was added taking water also to the latter from the Maas.

A problem has been the gradual raising of river beds to levels above those of the surrounding land owing to river sedimentation. After people first built river dykes to protect against flooding (the winter dykes), lower dykes were built inside them close to the river channel in summer. Between the summer and winter dykes, strips of land, the *uiterwaarden*, that were flooded in winter were available for pasture in summer. Slowly, however, the winter floods depositing clay raised the surface of the *uiterwaarden* and also deposited clay in the channels; and farmers often encouraged this process of clay deposition, which enriched the soil, by opening sluices in the low summer dykes in winter. Consequently, the *uiterwaarden* and water levels in the rivers during flood can now stand a metre or more above the surroundings.

4.3. River regulation in this century

The present century has seen the construction of several river barrages for water-level regulation, first in the Maas and later (1958-70) in the Rhine. The barrage near Arnhem now regulates how much water flows into the IJssel. The flow of water is important for flushing both the canals and the polders. In dry periods, more than 150m^3/s is needed to control the salinity of the surface water, rising to 650m^3/s to prevent salt intrusion in the Waterway at Rotterdam. The IJssel needs enough water to maintain freshwater conditions in Lake IJssel for agriculture in the northern provinces.

In the context of the Delta Plan, both coastal safety measures and the prevention of river flooding are paramount considerations. The dykes have to be raised to withstand the 1250-year event in river discharge: but the increase in their height is not without opposition from local inhabitants who see their village waterfronts about to be destroyed! In the case of Rotterdam, as well as dyke reinforcement, rebuilding of parts of the town at a higher level would strictly have been necessary, but as this was scarcely practicable, a storm-surge barrier is under construction in the Waterway (see section 3.4). When this is finished, the Caland canal (Fig.13.6) will have to be closed to keep the seawater out; as Rotterdam requires an enlarged Hartel canal for shipping going to the Maasvlakte, a second storm-surge barrier will have to be built in this canal.

Severe storms can also affect the water in Lake IJssel, and also in Lake Ketel which connects the river IJssel and Lake IJssel. The dykes here are still too low. To protect the area, a lock and storm-surge barrier will be built at Ramspol, due for completion by 2000.

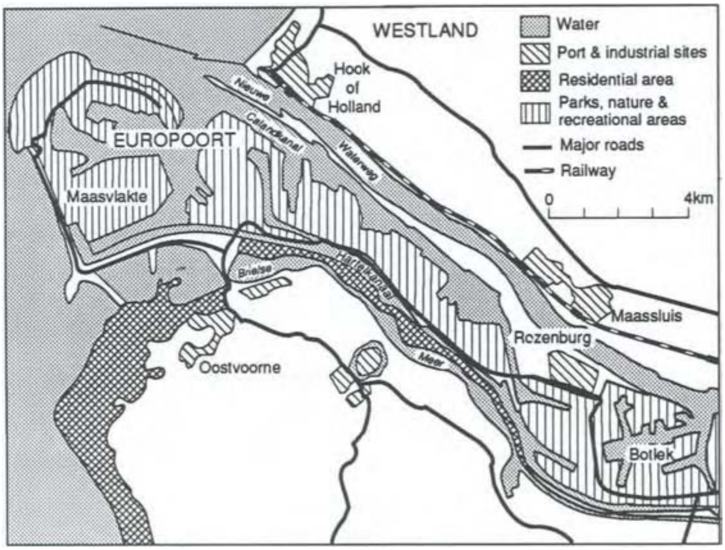

Fig.13.6. The western port areas of Rotterdam

4.4. Present-day hazards and problems

The policy regarding rivers has hitherto had two principal aims: to protect the land from flooding and to promote navigation. To these ends, dykes, canals and locks have been constructed, continuous channels in the summer beds of the rivers have been dredged, and sandbanks and bars removed.

The ever-present threat of river flooding, however, was dramatically highlighted by the events of the winters of 1993/94 and 1994/95, when part of the river valley of the Maas was inundated. In the winter of 1994/95 some 250 000 inhabitants and millions of cattle had to be evacuated from the floodplains of the Rhine, Waal and Maas west of Nijmegen. As a result of very hard work on the dykes, however, the area just escaped.

Now a new "delta plan" for the rivers has been started to raise and strengthen the dykes. In addition discussions have been started between the governments of France, Belgium and the Netherlands to regulate the water supply of the rivers. Due to canalisation, closure of water storage-basins and the effect on runoff caused by deforestation and enlargement of urban areas in all these countries, the differences in water discharge in the Netherlands have become more extreme.

The ice-jam danger on the other hand has now been largely eliminated by the regulation works - there have been no ice-jam floods this century; another factor in this has been the higher water temperatures related to discharge of cooling water from power stations, so that ice only forms now if air temperatures fall below -8°C for some time.

At present, the Rhine carries the heaviest traffic of any European river. It is also one of the most polluted, and river pollution has been a matter of increasing concern since the late-1960s. The sources of pollution are manifold: from domestic sources, excessive use of agricultural fertilisers, industrial pollution and pollution from shipping. Not only is the water polluted, but also the sediment borne by the river and carried into Lake Ketel (by the IJssel), the Hollands Diep (by the Rhine) and the Western Schelde. Measures have been taken to improve the water quality, which has certainly improved since 1970, but the problems of cleaning the sediment and sludge have not yet been solved. The problems are serious ones, for both river-water and, in the "high" Netherlands, groundwater have to be used for drinking purposes, as well as supplying water for agriculture and industry; and a falling water-table means that use of groundwater has to be drastically cut in exchange for greater extraction from rivers.

In 1987, the Rhine Action Programme was founded by the countries bordering the Rhine (France, Germany, the Netherlands and Switzerland) with the objective of improving water quality yet further by the year 2000.

4.5. The future

As well as the problems facing river management from future rise in sea level, a whole range of ecological problems has to be solved. The general aim is now to try to restore the rivers to a more natural condition while at the same time preventing flooding. More natural vegetation will be encouraged to develop along the banks and dykes. Some forest will return, and trees will be planted as borders to the meadows. Clay will be removed, perhaps 1-2m, from the *uiterwaarden*; former river channels will be excavated and re-used; and the formation of natural river banks rather than those armoured with concrete or stone will be another aim. Marshes and reed beds will be allowed to re-develop, and the general hope is that the ecological balance can be restored in respect of both plant, animal and bird life. Beavers have already been reintroduced! Eventually, it is hoped that the rivers can once again play a high-quality role in the ecology of the Netherlands.

5. Earthquakes

As in other relatively aseismic regions of Europe, the Netherlands very occasionally experiences slight earth tremors. Most may be related to a fault-system in the basement rocks that crosses the country from south-east to north-west. An unexpectedly large earthquake, magnitude 5.5 on the Richter scale, damaged and destroyed parts of Roermond and neighbouring villages in the south-east in 1992. An entirely different cause of minor tremors in the north-east is the extraction of natural gas, a process which also causes ground subsidence. If gas production should in future extend to the Wadden Sea, it is likely that artificial sediment dumping will have to be considered as a way of combating subsidence, which would have serious consequences in this low-lying area.

6. Soil erosion

The most southerly part of the country in the province of Limburg consists of limestone mantled with loess. Until 1950 or so, field sizes were small, with the steep slopes between the fields (*graften*) protected by bush vegetation, but since then, there has been a policy of field amalgamation and a change from grassland to arable farming. Maize and sugar-beet are now grown, rather than winter wheat, and farmers tend to plough the land perpendicular to the contours. After heavy rainfall, soil erosion is now emerging as a problem. Some villages have been invaded by streams of mud, while roads and drains have been blocked. There has been quite a lot of research into the surface runoff and erosion problems of this area, especially from Utrecht University (e.g. de Roo, 1993; Schouten *et al.*, 1985).

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* RIZA: Rijksinstituut voor Integraal Zoetwaterbeheer en Afvalwater-behandeling (Institute of Inland Water Management and Waste Water Treatment), part of the Rijkswaterstaat

NORWAY

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1. Introduction

Geomorphological processes may result in environmental hazards to people and society, and the consequences may vary from personal injury and minor damage, to disasters involving the death of many people and severe dislocation to the economy.

After some introductory remarks on terminology and on the range of processes and hazards encountered in Norway, the geomorphological processes will be considered in more detail. A historical review of the different types of hazard will illustrate such themes as their geographical distribution, the magnitude of the processes, the events and the damage caused, the timing of the events, their imprint on people and property, and the cost to society. Management aspects include the protection of people and property against the hazards, and the amount of aid and insurance available.

2. Terminology

Natural or environmental hazards involve many kinds of natural process, not only geomorphological but also other physical, chemical and biological processes. Some of these processes may be triggered by or strongly influenced by man. The term natural hazard originally meant an extreme process event, operating almost instantaneously or over a short period, giving rise to a catastrophe involving many deaths and severe damage to property. Nowadays the term is used in a wider sense to include lesser disasters and more general damage to the environment, people and property.

The effects of different geomorphological processes are not regarded as hazardous so long as they are spread out over time and do not seriously affect people, property and society in the short term. The normal work of rivers in erosion, transport and deposition, for instance, is not regarded as hazardous, but when that same river in flood begins to destroy property, the event is characterised as a disaster. Fortunately such situations are relatively rare in Norway. The slow, repetitive work of geomorphological and other processes may, however, in the long term cause damage to the natural environment. Weathering, for example, is a combination of geomorphological processes, and as acid rain strongly influences and speeds up these processes, weathering gradually changes the superficial deposits and alters the soil by removing nutrients from it, especially in southern Norway. It is open to question whether this should be considered a natural hazard.

In conclusion, the umbrella term "environmental hazards" includes all kinds of natural processes operating either slowly, repetitively and at low magnitude or rapidly at high magnitude in extreme events. These processes inflict damage on the natural environment, people and property; they can also be triggered by man, most often inadvertently. This article deals with only a part of the broad spectrum of natural hazards, namely, those related to geomorphological processes.

3. Geomorphological hazards in Norway

Of the total range of such processes, which include weathering (especially frost weathering and unloading), mass movement, and glacial, fluvial and marine processes, some may be particularly identified as potentially hazardous.

3.1. Mass movements

The principal phenomena included under this heading are rock falls, rock slides, debris slides and flows, clay slides and snow avalanches. Clay slides represent a combination of processes: the release of the slide may be due to differences in hydrostatic pressure within the clay deposit, and to basal fluvial erosion affecting the slope equilibrium. Snow avalanches sometimes involve only the snow layer, but most reach down to the bedrock and, by loosening fragments and transporting them, can play an important geomorphological role. Repeated use of avalanche tracks leads to the formation of avalanche chutes or rockfall funnels. Both clay slides and avalanches are sometimes triggered by man.

Mass movements are the foremost geomorphological hazard in Norway, and through the flood waves set up by some of them, are the most disastrous in terms of their impacts upon economy and society. In the national registers of physical damage, the *Norges Naturskadefond* (Norwegian National Fund for Natural Disaster Assistance; NDAF) puts rock falls and rock slides together in one group; another group comprises debris slides and clay slides; and a third group consists of snow avalanches alone. The *Norsk Naturskadepool* (Norwegian Natural Perils Pool; NPP), however, classifies all mass movements together as slides.

3.2. Fluvial processes

Under this heading are included fluvial erosional and depositional processes, flooding of low-lying country next to rivers or lakes, and ice jams on rivers. Erosion of river banks and the accumulation of coarse sediment where the gradient lessens are, together with flooding, responsible for the worst effects. The finer flood sediments may represent a nuisance in some cases, or may be of positive benefit in the farmers' fields. Ice jams in late winter or early spring can hold back snow meltwater; subsequent breaching of the jam releases a mixture of floodwater and river ice capable of effecting serious damage downstream. The NPP uses the term "flood" for events related to extreme river discharge, while the NDAF also includes ice jams in the category of river damage.

3.3. Wind and waves

Along most of the Norwegian coast, waves do not pose much of a threat to property as most of the coast consists of either rocky shores or boulder beaches. Quays and harbour installations in exposed localities are, however, at risk from the destructive forces generated by large storm waves which are also a hazard to boats used for recreation, anchored in marinas, and to shipping, as well as posing a threat to the lives of those working at sea. As there are few low-lying parts of the coast, storm surges are not a widespread threat, though they can prevent runoff and trigger flooding inland.

Strong winds occasionally damage coastal property and, in certain cases, forests inland; they can be a contributory factor in some cases of loss of life in the mountains and along the coast.

The NDAF puts damage due to strong winds and storm surges together; the NPP separates these two groups.

3.4. Other hazardous processes

The NDAF includes a group for damage caused by weight of snow, and a supplementary group for other causes. The NPP lacks these groups but has one for earthquake damage.

4. Prerequisites and controlling variables

This section will outline the physical prerequisites and variables affecting the spatial and temporal incidence of potentially hazardous processes in Norway. First, however, it must be stressed that geomorphological processes only become hazardous when they impinge on man and human activities. In this connection, the distribution of people is fundamental. A large part of the Norwegian population is concentrated in the coastal zone, and in the many valleys of western and northern Norway. Other densely populated areas are located in the agricultural lowlands of Trøndelag and Østlandet (for place-name locations see Fig.14.1 or 14.7). It is in such areas that the risks of loss of life or damage to property or infrastructure are greatest.

4.1. Rock falls and rock slides

The basic processes responsible are weathering and gravitational movement. It should be noted that many rock falls end up as rock slides lower down the slope.

In Norway, the principal weathering processes are frost action, related to climatic conditions, and unloading, related mostly to glacial erosion forms. The long, glacially overdeepened valleys of western and northern Norway (Fig.14.1, b), with their high relative relief, are prime sites for rock falls and slides caused by unloading. Changes in the internal bedrock pressures during deglaciation produced sets of joints in the bedrock

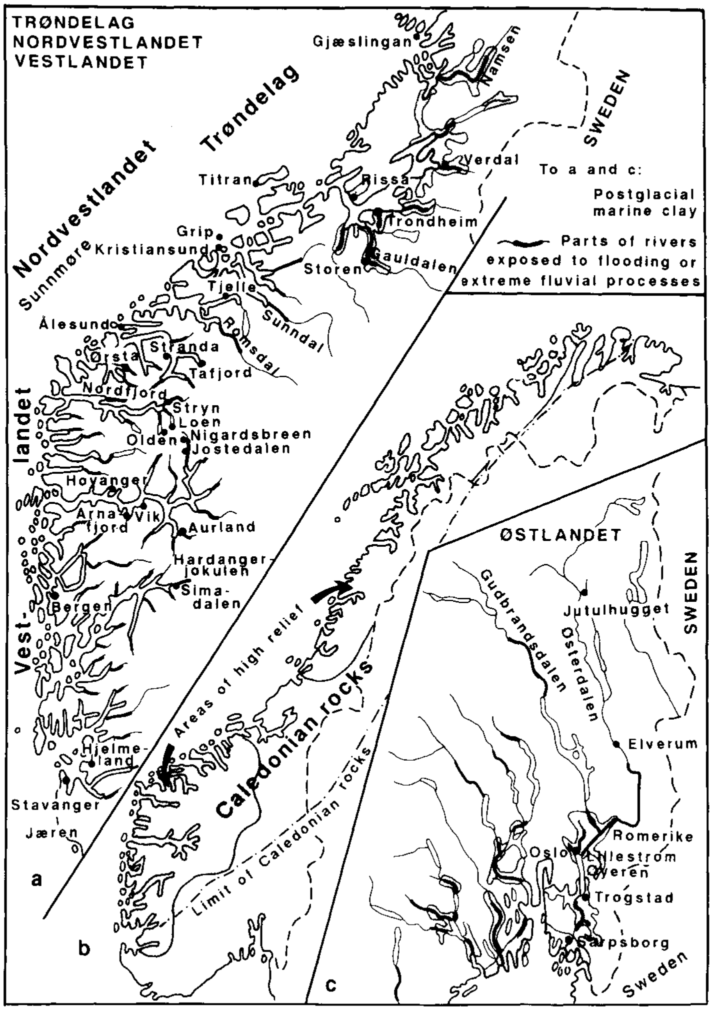


Fig.14.1. The distribution of Caledonian rocks and areas of high relief (b); areas of post-glacial marine clay (a and c), and generalised map of river segments affected by extreme fluvial processes or flooding

roughly parallel to the ground surface (dilatation joints). These fractures, together with joints of other origin (e.g. tectonic) and bedding planes provide sites for frost action to exploit them. Other rock characteristics relevant to weathering include grain size, porosity and permeability.

Most bedrock in Norway has a joint system; some large structures are related to the Caledonian orogeny with its north-east to south-west trends. The igneous and metamorphic Caledonian rocks of the western and north-western parts of southern Norway, and also farther north in northern Norway (Fig.14.1, b), along with the Permian igneous rocks of the Oslo region are the main lithologies exhibiting mass movement activity. In other rock types, which tend in any case to be associated with areas of lower relief, mass movements are fewer.

Another important factor in rock weathering is the presence of water. If the hydrostatic pressure of groundwater in the joint system increases, the internal strength of the bedrock is reduced. Presence of water in the joints is vital also for freeze-thaw (frost) action; repeated stressing of the rock in this way slowly reduces its internal strength.

Freeze-thaw weathering also depends on the temperature regime, especially the number and amplitude of variations around 0°C, which occur most often in autumn, winter and spring. Along the coast as far north as Trøndelag, the mean monthly temperature during winter is close to 0°C, but the short duration of freezing conditions and lack of severe frost do not favour frost action. Moving a little inland and especially to higher elevations in the valleys and mountains, the period favourable for frost weathering increases to 2-3 months a year; together with the prevalence of unloading joints, conditions combine to encourage loosening of material on slopes.

4.2. Debris slides and flows

The main prerequisites are steep slopes with a cover of loose unstable material. Till covers are particularly prone to instability, with their variable thicknesses, varying grain size and frequent liability to waterlogging. Excessive water content is, in fact, often the cause of movement, once pore pressures have reached the critical threshold. Other triggering factors can include water drainage along the slope or loading of the debris cover with other material falling from higher up the slope.

4.3. Clay slides

Marine clays, of considerable thickness in places, were deposited in the Late- and Post-glacial seas and later uplifted with the post-glacial rebound, so that in places they now extend some distance inland from the coast (Thoresen, 1991). The main areas are found in Trøndelag around Trondheimsfjorden and around and to the north of Oslofjord (Fig.14.1, a and c). When the internal water pressure in these clays increases, the bonding between the clay particles is reduced, so that the weight of the clay itself can then generate a slide. The movement of fresh groundwater through the marine clay will also slowly lower the salt content, further reducing the electromagnetic bonds between the particles. The clay becomes a quick clay, meaning that it is sensitive to any further imposed stresses and liable to move (Rosenqvist, 1960). Additional stresses may include river erosion of the slope toe, man's activities (especially heavy load transport vibration, and loading with other material) or simply the weight of the overlying clay itself. As the water content of the clay and the movement of water through it are critical factors in its susceptibility to sliding, many clay slides take place during either spring snowmelt or heavy rainstorms in autumn.

4.4. Avalanches

The occurrence of avalanches depends on the presence of abundant snow, and almost all the country may be affected, but especially the western and northern areas with their more exposed position in terms of snow-bearing winds. The second prerequisite is steep slopes. High relative relief (see Fig.14.1, b) also provides opportunities for accumulation of deep drifts in leeside positions on many fjord and valley slopes. The accumulation of deep snow and its metamorphosis during the winter are major factors in the stability of the snow cover; this makes the meteorological conditions which transform the snow prior to the release of an avalanche the most fundamental variable.

4.5. Floods and ice jams

As most Norwegian drainage basins have one or more lakes, and as there are only relatively small low-lying areas beside the rivers, flooding is not a widespread hazard. During exceptional rainstorms, however, and especially in the western and northern areas, flooding may occur in basins with only a few small lakes or none at all; and a few areas of low-lying land along the rivers in Trøndelag and in Østlandet (Fig.14.1, a and c) become hazardous during spring snowmelt. Apart from flooding, more serious damage is often caused by overbank sedimentation and bank erosion, related to raised water levels and high velocities.

The prerequisite for ice jams is a channel and valley configuration favourable to the development of river ice followed by temporary blocking of the channel. Melting snow and ice add to the water behind the dam until a break-through occurs, when the valley downstream may be flooded with water and broken ice floes, causing great damage to property.

4.6. Storms and storm surges

The main variables here are meteorological. Most strong winds affecting Norwegian coasts are generated by North Atlantic depressions, and coincidence between onshore storms, high tides and low barometric pressure can raise coastal water levels considerably. Damaging effects are limited to a few low-lying coastal areas and exposed harbours (Kvale, 1960).

4.7. Earthquakes

The location of Norway 1000km or more from the western edge of the Eurasian tectonic plate means that it is not a seismically active area. Some small earthquakes are mostly related to glacio-isostatic rebound, or possibly to the aftermath of Tertiary uplift.

5. Hazardous events: magnitudes, processes and damage caused

5.1. Rock falls and rock slides

Rock falls are numerous, but most go unrecorded and only occasionally do they do any harm to people or property. Information on rock slides is somewhat better but far from complete; much information is unpublished and only recorded in farm or parish books. For earlier times the data are also rather uncertain (e.g. in about 1630, a rock fall along the Innfjord killed all the people on one farm). Only the more recent events, or the larger disasters, are properly recorded (Svendsen and Werswick, 1961) (e.g. on 8 January 1731, part of Skafjellet (*fjellet*: mountain) at Stranda in Sunnmøre fell and destroyed a farm, killing 17 people; and around 1830, a rock slide in the Lyngen area of northern Norway killed 19 people).

The main rock slide disasters in Norway, which are also the best known, are the two slides in Loen and the one in Tafjord, but first the rock slide at Tjelle in Langfjorden, Romsdal, should be mentioned. This happened in March 1756 and resulted in 32 deaths. With a volume of approximately 12 million m^3, it is the largest known rock slide in Norway, but there is no further information about it.

The Tafjord event in Sunnmøre took place on 7 April 1934. Close to one million m^3 of material fell from a height of 700 - 750m on to the Heggeurda talus below; about 2 million m^3 entered the fjord and produced three large flood waves. The largest of these reached 62m above sea level, and even 7km farther down the fjord at Sylte, the main flood wave was 4m high. The flood waves which in a short time reached the small community of Tafjord, 5km up the fjord from the site of the slide, rose to 15.6m. Quays and boats, as well as houses and bridges close to the sea, were destroyed, pushed up on land or washed out to sea. The death toll was 41.

The Loen events (Nesdal, 1983) took place on 15 January 1905 and 13 September 1936, both on the same mountain slope (Fig.14.2). In the first of these, 61 people were killed by the flood wave, and in the second, 74. In 1905 a part of the rock wall, 100m high, 50m broad and 10m thick (altogether about 50 000m^3) and 500m up from its base fell down on to the talus below, and a total of about 300 000m^3 of debris entered Lake Lovatnet. The falling debris produced several flood waves and set up standing waves in the lake basin to the north-west. At Nesodden (both *nes* and *odde*: headland), opposite the rock slide, the main flood wave reached a height of 25m above the lake, split into two and the one moving south-east was 40m high when it was reflected below the Bødalsfjellet. The reflection of the wave absorbed some of its energy so that farms in

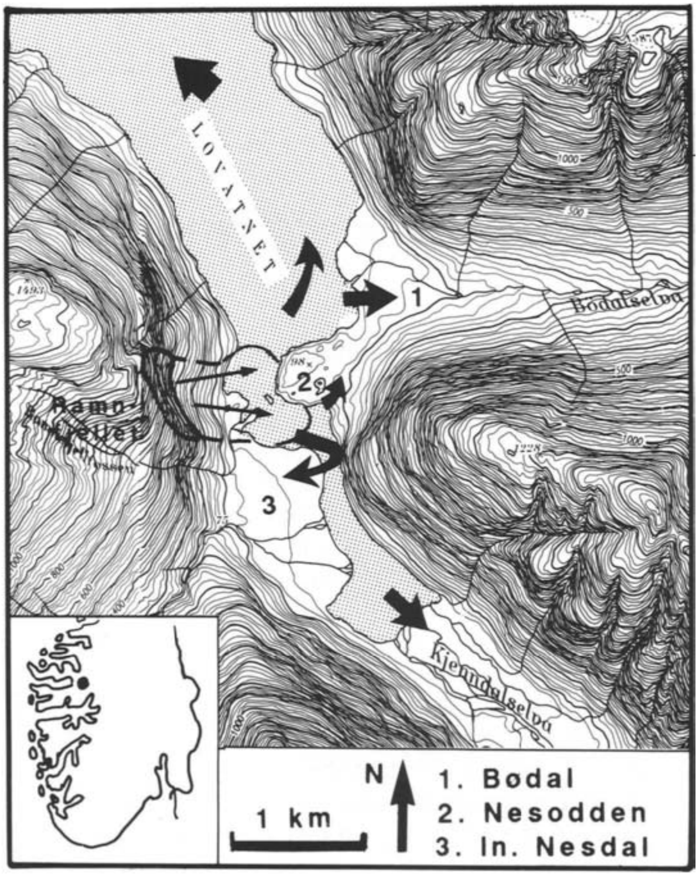


Fig.14.2. The Loen rock slides from Ramnfjellet, 15 January 1905 and 13 September 1936. The flood waves of the 1905 event are indicated.

Inner Nesdal (*dal*: valley) were not affected, and in the south-east of the lake the flood wave only reached 3m. The main flood wave moving north-west rose to 15m at Bødal, while farther along it only reached 2-3m. At the north-eastern and northern end of the lake, at Sæten, its height increased to 5m. At Nesodden, the small ferry boat Lodal was thrown inland for 350m, ending up 15m above the lake.

A small rock slide took place about a month after the first Loen event, without doing any great damage. It was said at the time that a disaster like the great rock slide could not happen again at the same place. However, the prediction was wrong, and in 1936 a huge slide again occurred, this time in September when the lake level was at its highest. During the late summer of 1936, there were many minor rockfalls from the mountain face; but the major event on 13 September involved 1 million m^3 of material falling from a height of 800m. This slide produced several flood waves in the lake, the highest reaching no less than 74m at Nesodden. It destroyed all the farms at Bødal (wave height 31m) and washed away all the soil at Nesdal (wave height 23m). The wreck of the Lodal was moved a further 150m inland and came to rest at a height of 50m above the lake. At the north-western end of the lake, at Sæten, the wave was 15m high.

Between 21 and 22 September, a further rock slide occurred, and on 9 November three rock slides moved almost as one, which was in total larger than the slide of 13 September. The flood wave was as large as the highest previous one. In this incident no one was killed, but a new bridge at Sæten and some new boats on the lake were destroyed.

The bedrock of Ramnfjellet is varied, granite gneiss and quartzite being the main rock types, while locally in the rock wall bands of mica and hornblende are to be found. These weather more easily than the quartzite and gneiss, and it is along these layers that groundwater emerges from the rock wall. After the catastrophe of 13 September, large quantities of water were seen to be coming out of the wall. Possibly, loose material had temporarily blocked the escape of water, allowing water pressure to build up. High water pressures may have been the triggering factor in the 1936 slide, but frost weathering was said to be responsible for the 1905 slide.

A spectacular ice fall in Krundalen, a tributary valley of Jostedalen, took place in August 1986 (Ryvarden and Wold, 1991). Ice blocks amounting to 250 000t broke off the Baklibreen (*breen*: glacier) and fell 700m into Krundalen. Three Dutch tourists were killed.

5.2. Debris slides

Debris slides are not often recorded as they mostly give rise to only minor damage, or else coincide with rock falls, heavy rain or floods. The most celebrated major debris slide event in Norway was the catastrophe named *Storofsen*: literally, the large (rainstorm) disaster. Storofsen happened in August 1789 in the central part of Østlandet, southern Norway, in Gudbrandsdalen and adjoining valleys. The autumn of 1788 was rainy and followed by a winter which was mild but snowy. Spring melting of the abundant snow was succeeded by a rainy summer, so that the soil became highly saturated. Finally, a rainstorm in August 1789 triggered mass movements on the slopes of the main valley and its tributaries. Numerous scars and V-shaped ravines testify to the activity of the numerous debris slides that took place then. There was also extensive river flooding, and the total death toll in Gudbrandsdalen reached 68.

Many smaller debris slide events are known to have occurred in various parts of Norway, responsible for a few deaths, 2, 3 or 4 people in each case.

5.3. Clay slides

The biggest known clay-slide disaster in Norway was the one that took place in Gauldalen, 5km east of Støren, Trøndelag, on 14 September 1345. It formed a dam across the river, producing a temporary lake stretching up-valley for 14km. Eventually the water overtopped the clay dam, cutting into it rapidly and causing a flood downstream for nearly 40km, destroying 40 farms and seven churches. It is said that 250 inhabitants died, and probably an equal number of poor people and travellers along the road at the time.

At the waterfall of Sarpfossen at Sarpsborg, the manor of Borregaard was destroyed by a clay slide on 14 February 1702; 14 people were killed and an uncertain number of servants.

Verdalen in Trøndelag has repeatedly been the location for many small and a few larger clay slides. On 21 September 1726, eight people were killed; in 1747, five. The largest event, however, took place on 19 May 1893, when the scar left by the slide extended over 2.9km^2 and the slide itself covered an area down-valley of 8.6km^2. In total, about 55 million m^3 of clay moved down the valley from the Follo area: 16 farms were obliterated and 30 others badly damaged. Of the 250 people living on the farms, 112 were killed. The river was also dammed, forming a temporary lake whose bursting on 21 May produced a flood down-valley.

On 23 April 1870, seven people were killed by a clay slide at Hokstad on Ytterøy, while there were eight deaths on 6 December 1898 due to a clay slide in Målselvdalen, northern Norway. Some recent examples include the following:

7 November 1953	Bekkelaget (Oslo region)	death toll 5
7 May 1959	Nordreisa (northern Norway)	death toll 9
29 October 1967	Trøgstad (Østfold)	death toll 4

In the latter event, quick-clay flows and flooding affected 14ha, even though the scar occupied only 3.6ha; 10 houses and three commercial buildings were destroyed.

The Verdalen event of 1893 demonstrates the different stages of a clay slide. First, the initial slide itself creates a scar; then the moving masses of quick clay cause damage down-valley; thirdly, the river is blocked forming a lake drowning the valley behind the slide; and finally the valley below is flooded as the lake bursts and empties.

The Rissa clay slide (29 April 1978), the largest in Norway this century (Gregersen, 1981), supplements this story. It covered an area of 33ha and contained 5-6 million m^3 of clay. Figure 14.3 shows its development. It was initiated at farm A where about 700m^3 of material was excavated in two days in connection with construction of a new wing to the barn, and dumped at the shore of Lake Botnen so as to extend the farm area. Dumping was stopped when about half of the deposited material stretching 70-90m along the shoreline (1 on Fig.14.3) slid out into the lake. The edge of it was 5-6m high and extended inland for only 15-25m. This small slide, however, triggered a second phase: liquefaction of the neighbouring quick clay which started to flow into the lake during the next 40 minutes. The scar retreated headwards to form a narrow wedge 450m long as far as farm B (2 on Fig.14.3), the slide now covering about 3ha, but it turned out to be only about 8 per cent of the final slide area.

The third phase was the real hazard because phase two had destabilised the area inland and initiated two flake-type slides. The first of these (3 on Fig.14.3) involved a

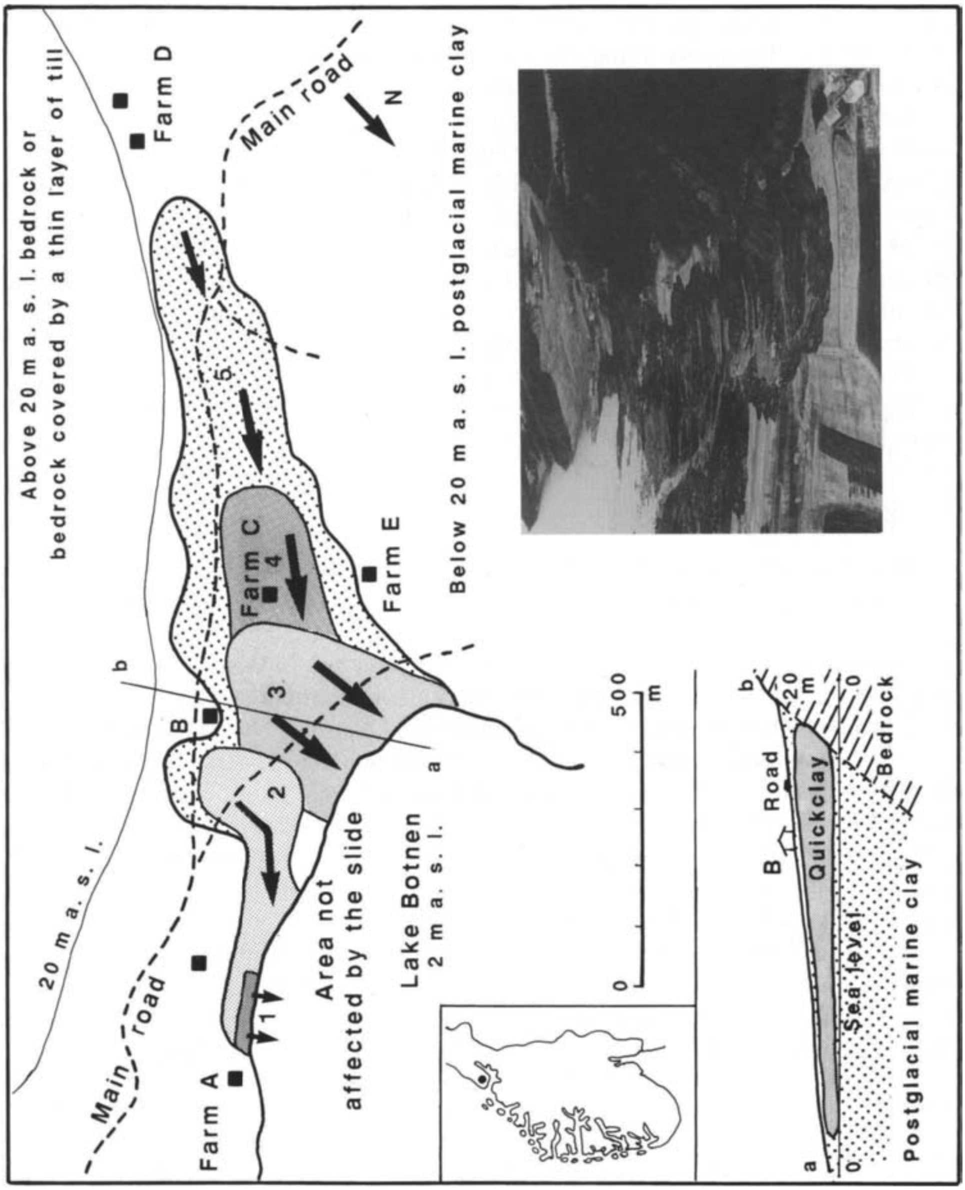


Fig.14.3. The Rissa clay slide of 29 April 1978. Photo: Aftenposten

clay raft 150 x 200m in size which slid into the lake at a speed of 10-20km per hour, carrying some buildings of farm B with it. The second (4 on Fig.14.3) was as large as the first but moved more quickly (30-40km per hour) taking the whole of farm C with it. The owner stood on safe ground watching it happen; it was also filmed by an amateur photographer. These two rapid movements were followed by several smaller slides developing the scar retrogressively towards farm D.

From the initial slide near A, the whole sequence took about 45 minutes, but the third and final phases took only 5 minutes. The distance from farm D to A is about 1.5km. The whole area was agricultural land. Seven farms and five family houses were either destroyed or had to be abandoned. Only one person unable to move quickly was killed, even though there were 40 people in the area at that time. The long time taken by the second phase made people aware of the danger and gave them the chance to move to safe ground. Material entering Lake Botnen set up one large and several smaller flood waves which damaged a few buildings on the opposite shore of the lake.

The Verdal and Rissa clay slides provide important information about many aspects of these potentially dangerous phenomena, and the latter event makes it quite clear that man can be the triggering agent.

5.4. Avalanches

Most reported avalanches involving loss of life have a death toll of 2-5 people. There have been, however, a few larger events, associated with certain avalanche funnels, areas or particular winter periods. At Arnafjord in Sogn, for example, one avalanche on 2 December 1811 killed 43 people. Some areas, notably the valleys of Sunndalen, Olden and Stryn, have suffered repeatedly; the areas along Hjørundfjord, east of Ørsta, have been particularly vulnerable with 27 people being killed in 1770. The villages of Ørsta and Volda have been severely affected. In 1679, the Sunnmøre district lost 130 people in avalanches, while in 1868, one of the worst years, 161 were killed, mostly in Nordfjord, Sunnmøre and Romsdal. Other bad years were 1881 (60 killed); 1895 (24); 1906 (29); 1918 (29); and 1919 (31). During Easter in 1947, 11 tourists were killed, marking a change from the past in which the normal casualties consisted of farm workers or people travelling through the valleys.

Exceptional occurrences include the avalanche that took place on the asphalted frontal slope of a hydro-electric power station dam (one person killed); and the death of a skier and injury to others in an avalanche triggered by them on a relatively gentle slope in an area cleared of forest in the lowland of Vestfold.

5.5. Floods

As already mentioned, some flood disasters have been caused by clay slides temporarily blocking a valley - as in Verdalen in 1893 and in Gauldalen in 1345. The Gaula river, however, like many others in Norway, has also experienced floods unconnected with clay slides, for example in 1918, 1940 and 1944.

The rivers entering the north of Lake Øyeren (southern Norway; Fig.14.1, c) have for years posed the threat of flooding to lake-shore settlements, the floods being produced by snowmelt in the mountains. In late spring, both in 1966 and 1967, low-lying areas here and especially the small town of Lillestrøm suffered extensive damage.

The Storofsen of 1789 was a combination of debris slides and floods. In Jostedalen in August 1979, the preconditions were much the same as those of the Storofsen, but the result was mainly a large flood, even though some of the movement of the material may have started as a debris slide. There was no loss of life, but damage to property was tremendous. Similar weather conditions, flood events and ensuing damage have probably occurred repeatedly in western Norway (Grove and Battagle, 1989), and were probably also particularly frequent in the Little Ice Age.

One of the outlet glaciers of Jostedalsbreen, Nigardsbreen had an outburst of subglacial water trapped by a collapsing tunnel; the flood almost cost the lives of tourists visiting the glacier at the time, and one person was killed by falling ice blocks. In 1743 (during the Little Ice Age), Nigardsbreen was advancing, destroying several farms and their fields, though today its snout lies 4.5km up-valley from its 1743 position. At Svartisen in northern Norway, the snout of Austerdalsisen dammed the lake of Austerdalsvatn (*breen, isen*: glacier; *vatn*: lake). The lake drained suddenly beneath the glacier into Røvassdalen in 1941, doing great damage to property. Later, an artificial tunnel was constructed to eliminate the danger. There was a similar situation at the Hardangerjøkulen (*jøkulen*: ice cap, glacier) where the Rembesdalsskåki outlet glacier holds up the Nedre Demmevatn (Liestøl, 1960). In August 1893 the lake drained subglacially for the first time, the flood doing much damage to property in Simadalen. A tunnel was also constructed here, but the flood recurred in August 1937. Its magnitude was less because of the tunnel, but even so, the lake drained in 3-4 hours and a flood wave 20-30m high swept down Simadalen. Some 20 buildings were destroyed and 50ha of agricultural land were covered with coarse debris. Fortunately the flood happened while farm animals and people were at the summer farm in the mountains, and there was no loss of life.

5.6. Storms and storm surges

Strong winds in themselves are counted as meteorological rather than geomorphological hazards, but generate storm waves that can cause loss of life and damage to coasts. The storm of 23 February 1625 caused 210 deaths in the coastal waters around Gjaeslingan, Vikna, but the loss of life was the result of use of open boats for fishing. Other severe storms occurred on 2-3 March 1906 (31 people killed in the same area), 13-14 October 1899 (140 deaths, near Titran on Smøla), 14 January 1920 (37 deaths, also near Smøla), and 21-22 January 1901 (35 deaths, Sandsundvaer).

5.7. Earthquakes

Earthquake damage is rare and of quite minor importance in comparison with the other hazards described. It is just worth mentioning one recent example. On 23 January

1989, the area along the west coast, near the mouth of the Sognefjord, experienced a small earthquake with an epicentre at the Solund Islands. Little damage was done, but the disturbance was noticed even in Oslo and other places in southern Norway, and the NPP later registered it in its accounts.

5.8. Other hazards

Other geomorphological hazards registered by the NDAF or NPP include damage by drifting sea ice along the coast of Finnmark, and submarine landslides in Ålesund harbour. Another geomorphological hazard that has not been so far mentioned is that owing to an advancing glacier. One of the few examples of a valley glacier advancing in the Little Ice Age is Nigardsbreen (the "Nine Farms Glacier"), an outlet glacier from the Jostedalen plateau glacier. Nigardsbreen (Fig.14.1) destroyed eight of the nine farms and farmland in the Jostedalen valley in the 1740s (Liestøl, 1960).

6. Types, costs and regional distribution of geomorphological hazards

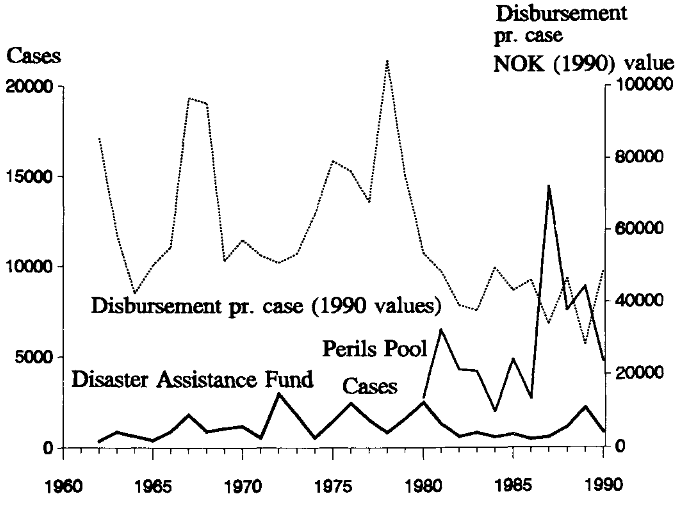
Thanks to the information collected by the Norwegian National Fund for Natural Disaster Assistance (NDAF) since 1962, and the Norwegian Natural Perils Pool (NPP) since 1980, it is possible to analyse trends in the occurrence of hazards over recent years.

The NDAF has dealt with a total of 29 840 cases in the years 1962-90, the NPP with nearly 63 000 cases in 1980-90. Fig.14.4 shows the variations in the number of cases per year. The greatest number dealt with by the NDAF was in 1972 (2968) whereas only 370 were registered in the starting year 1962. The years 1976 and 1980 each had about 2500 cases, but the mid-1980s relatively few. In the case of the NPP, the total number has varied between 2000 and 14 500 (1987). There is no distinct trend in the NDAF curve, but the NPP curve may show an increase. This, however, may be due to lack of public knowledge of the NPP in its early years.

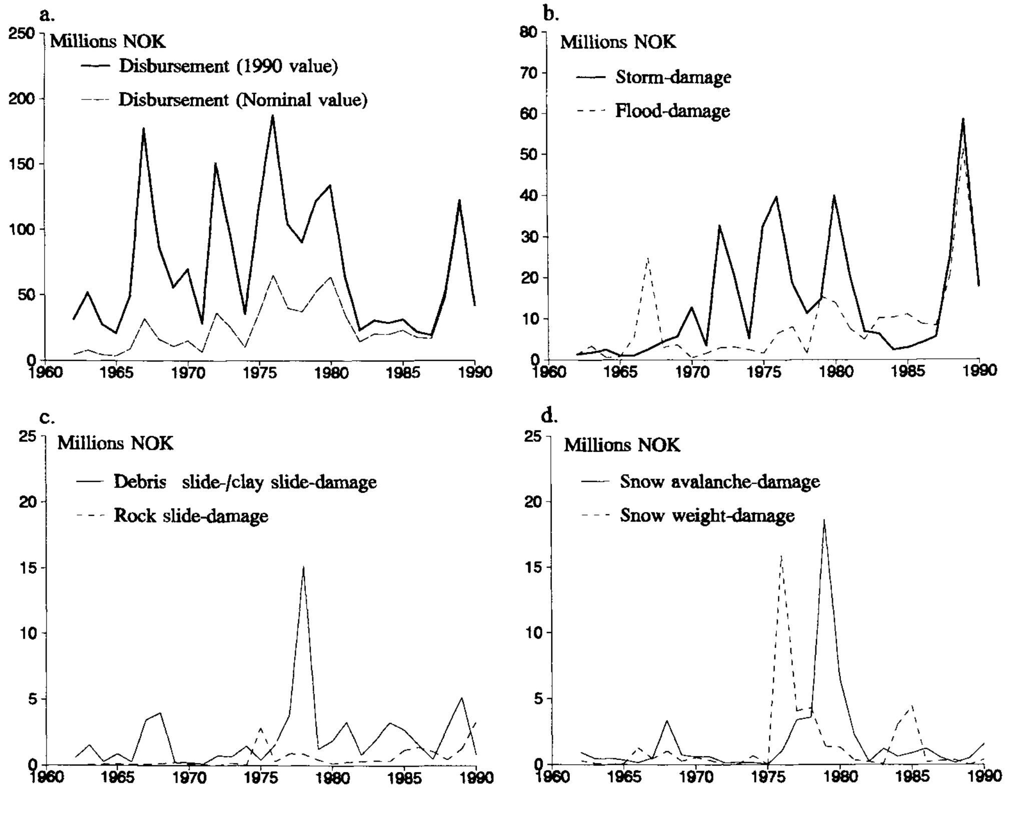
Disbursements from the NDAF (Fig.14.5, a) rose to a series of peaks in 1967, 1972, 1976, 1980 and 1989. The graphs show both nominal values and their 1990 equivalents (NOK = Norwegian Kroner; exchange rate in 1990 approximately 1 US $ = 7 NOK). [When not otherwise indicated, all figures quoted are in nominal values.] In the peak year 1989, disbursements reached 120 million NOK, and in total the NDAF has paid out 780 million NOK.

Fig.14.4. (*facing page, upper figure*) Disbursements by the Norwegian National Fund for Natural Disaster Assistance (NDAF), 1962-90, and by the Norwegian Natural Perils Pool (NPP), 1980-90. The dotted line also shows disbursements by the NDAF per case (1990 values).

Fig.14.5. (*facing page, lower figure*) Disbursements by the Norwegian National Fund for Natural Disaster Assistance for the period 1962-90 (a), and breakdown according to type of natural process (b, c, d). Values shown on b, c, and d are nominal values.



Cases
Disbursement pr. case NOK (1990) value
Disbursement pr. case (1990 values)
Perils Pool
Disaster Assistance Fund
Cases
20000
15000
10000
5000
0
100000
80000
60000
40000
20000
0
1960
1965
1970
1975
1980
1985
1990



a.
Millions NOK
Disbursement (1990 value)
Disbursement (Nominal value)
b.
Millions NOK
Storm-damage
Flood-damage
c.
Millions NOK
Debris slide-/clay slide-damage
Rock slide-damage
d.
Millions NOK
Snow avalanche-damage
Snow weight-damage

Disbursements by the NPP for 1980-90 totalled 1660 million NOK, with the highest in 1987 - 612 million NOK, mainly owing to a severe storm with heavy damage. In December 1991 there was an even worse storm which reached a maximum on 1-2 January 1992, centred at Møre og Romsdalen (county 13 in Fig.14.7). One week later, a preliminary calculation assessed the damage at more than 600 million NOK, with a further 400 million NOK for forest damage. This serves to place such an extreme storm in perspective: the single storm in the first two days of 1992 will cost more than the NPP paid out in its previously most expensive year (1987); and more than the total pay-out from the NDAF since this started in 1962!

6.1. *Types and costs of hazards*

The disbursement per year for the NPP has a mean of 150 million NOK; for the NDAF, the figure is 27 million. In terms of the mean disbursement per case, the figure is about 26 000 NOK, for both sources of finance. The nominal disbursement per case for the NDAF rose from 7000 - 9000 NOK in the first half of the 1960s, to 25 000 - 40 000 NOK in the late 1980s. Figure 14.4 shows a declining trend of about 1000 NOK per year in disbursements per case expressed in 1990 values (dotted line).

In respect of the different types of hazard, the proportions of money spent on each by the NDAF are as follows:

Storms	48%	Avalanches	7%
Floods	27%	Weight of snow	6%
Debris and clay slides	8%	Rock slides	2%

For the NPP, the corresponding figures are:

Storms	64%	Storm surges	7%
Floods	17%	Earthquakes	0.2%
Slides and avalanches	11%		

The figures of the NDAF (Fig.14.5, b) show that damage caused by storms was at a low level in the 1960s and 1980s, except for the two bad years of 1980 and 1989. In the 1980s this may be related to the inception of the NPP. For flood damage, 1967 was a bad year, especially in the Lillestrøm area. 1987 was considerably worse, when the NPP paid out 273 million NOK. The data for the various types of slide (Fig.14.5, c) show no clear trends except for the one bad year of 1978 when 15 million NOK were paid out for damage resulting from debris and clay slides. In relation to snow damage, the pay-out by the NDAF was small until the late 1970s (1976: snow weight damage cost 16 million NOK; 1979: avalanche damage cost 18 million NOK). Storm surges cost only low disbursements by the NPP except for the bad years of 1987 (134 million NOK) and 1990 (34 million NOK). Earthquake disbursements amounted to less than 100 000 NOK in most years, but 1.6 million NOK in 1989.

6.2. Regional distribution of hazards

Figure 14.6 shows the regional distribution of hazards by county (1-18: see Fig.14.7; note that Oslo and Akershus counties are combined as no.1). Total disbursements are given in Fig.14.6a; Fig.14.6b,c,d show a breakdown according to type of hazard. In respect of the counties 1 (Oslo/Akershus) and 7 (Telemark), the year 1987 was exceptional, as noted above, for severe rain storms, wind damage and storm surge. The cost for Oslo and Akershus was 195 million NOK, and for Telemark 92 million NOK. All other values for total disbursements per year are below 5 million NOK. If the high 1987 values for Oslo/Akershus and Telemark for 1987 are omitted, a regional breakdown

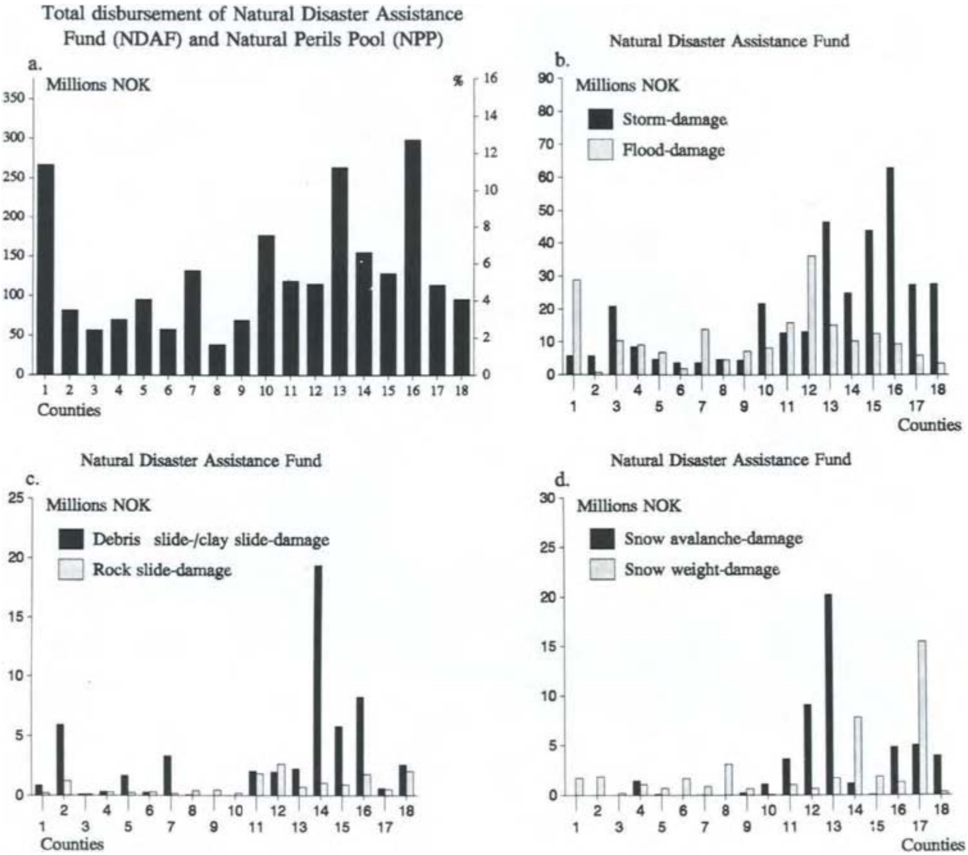


Fig.14.6. Regional distribution by county of the disbursements arising from different types of hazard. a: all types together for both the NDAF (1962-90) and NPP (1980-90). b, c, d: breakdown according to type of hazard.

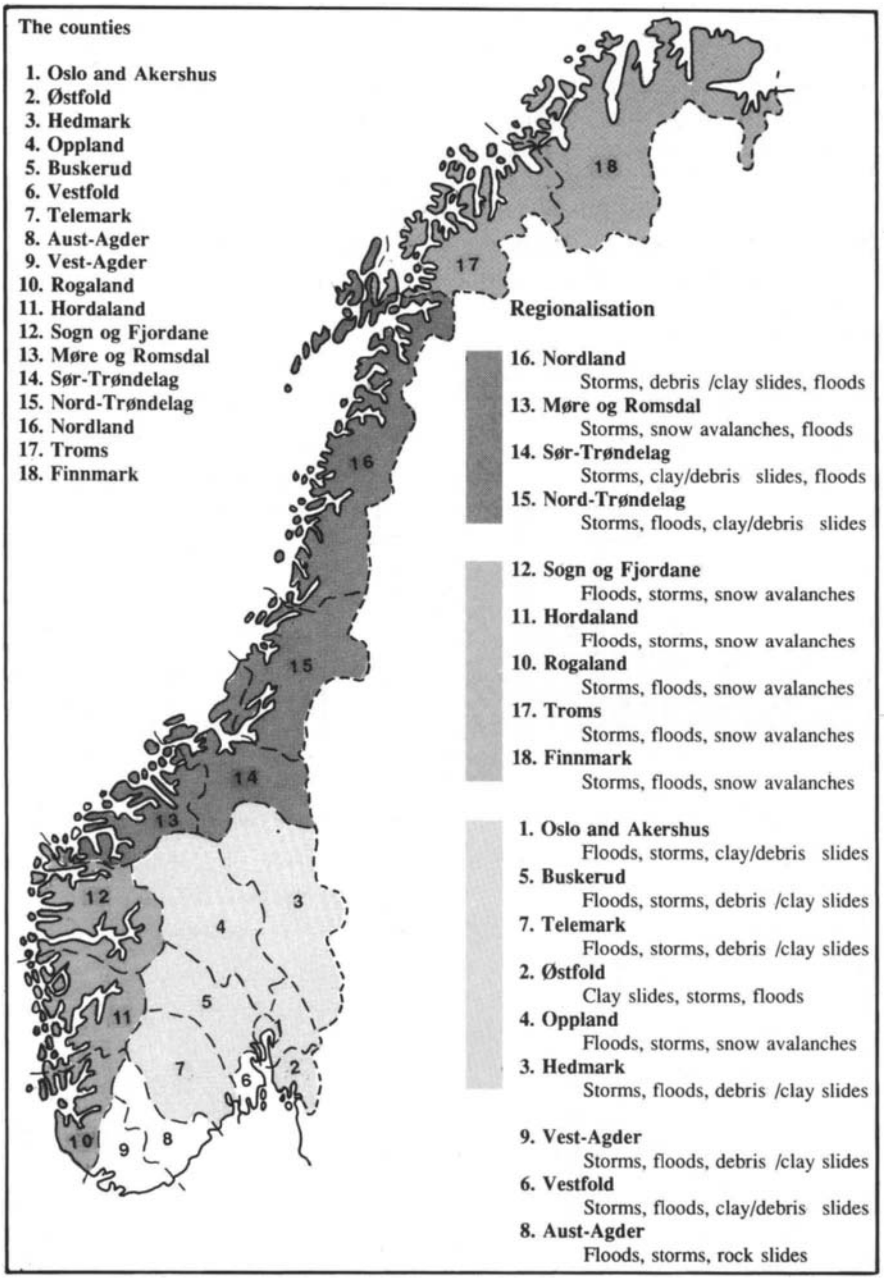


Fig. 14.7. Regional distribution, by county, of geomorphological hazards in Norway

into two groups of nine counties each is significant. The first group is in the south-east (1-9: see Fig.14.7) where the total disbursement for the NDAF and NPP together was 874 million NOK; the second covers western and northern Norway (10-18) with 1474 million NOK.

The length of coastline belonging to each county and the numbers of people living in the coastal zone are important factors in the degree of hazard. Counties 1-9 have a coastline of 2385km, 11% of the total (5841km if islands are included); counties 10-18, in contrast, share 18 726km or 89% (47 228km including islands). Nordland has the longest coastline of any county: 4250km (13 998km with islands). The length of coastline and its degree of exposure to the Atlantic clearly influence the storm-damage pattern.

Figure 14.6a allows a further level of regionalisation to be established. In the south-east, counties 6, 8 and 9 suffer least from all hazards. In western Norway, counties 10, 11 and 12 in the south, and 17 and 18 in the north are strongly affected, while counties 13-16 suffer most severely.

Storm damage (Fig.14.6b) is mainly concentrated on the coast. Rogaland (10) and the counties from Møre og Romsdal (13) northwards, are most severely affected by strong winds, Nordland being the worst affected. In judging the relative costs of damage, however, it must be remembered that the population pattern is as important as the meteorological situation: more people live in some sectors, e.g.Rogaland, than others.

Flood damage is the primary type of geomorphological hazard in the western counties of Hordaland (11) and Sogn og Fjordane (12), where severe flooding, bank erosion and overbank deposition of coarse debris are related to heavy rainstorms such as that of 10-11 January 1992. Other counties where flood damage is the primary hazard are in the south-east (1, 4, 5, 7 and 8). Here there are more extensive low-lying areas and larger river basins than in Vestlandet; in the latter, rivers are generally shorter, steeper in long profile and flow in more deeply incised valleys. Vestlandet also receives higher precipitation because of its position in the path of south-westerly winds.

Damage caused by clay and debris slides (Fig.14.6c) is concentrated mainly in Østfold (2) and in the neighbouring counties of Sør-Trøndelag (14), Nord-Trøndelag (15) and Nordland (16). In the first three, it is mainly a question of damage from clay slides, related to the presence of post-glacial marine clays. In Nordland, damage is chiefly from debris slides, favoured by areas in which till and strong relief occur together.

Rock-slide damage (Fig.14.6c) is centred in the west (11-12), followed by Finnmark (18) in the far north. In the total of geomorphological hazards depicted by these data from NDAF and NPP, rock slides occupy a surprisingly minor position. Only in Aust Agder (8) is it the third most important hazard in terms of cost of damage, but in this county the cost of all hazards together is only small. In comparison with the damage inflicted by storms, floods and avalanches, rock slides and rockfalls have only a low impact, despite the well-known catastrophes at Loen and Tafjord.

Avalanche damage (Fig.14.6d) reaches its maximum in Møre og Romsdal (13), with counties 11-12 and 16-18 also registering considerable effects. In counties 9, 11, 12, 17 and 18, avalanches are the third most important hazard; in Møre og Romsdal it is the second most serious hazard (after storms and floods). Damage from weight of snow is most pronounced in Troms (17), but there is a scatter in other counties (2, 6, 8 and 14). The cause of this distribution is probably connected not with meteorology but with the age and type of buildings involved, such as barns. The presence or absence of Building Codes or planning controls also affects the distribution.

Earthquake damage which accounts for less than 1 per cent of the total disbursement (and is included only after 1980, in the NPP) is found on the west coast in Sogn og Fjordane (12) and Nordland (16).

7. Hazard management

There are three aspects of the management of natural disasters and potential hazards. After a catastrophe, there is an immediate need for relief work and first aid, which is the responsibility of organisations such as the police, fire brigades and the military, as well as of non-governmental organisations such as the Red Cross and Norwegian Peoples' Aid. Secondly, there is the reconstruction work and restoration funded by insurance or grants from bodies such as the NDAF and the NPP. Thirdly, management involves efforts to mitigate the effects of potential catastrophic processes, including warning systems, hazard zoning and the construction of protective works.

In the reconstruction of the country after the Second World War, it soon became clear that some rebuilding had been undertaken in places at risk from geomorphological hazards. Society had to help, and grants were given through the Ministry of Agriculture. In the 1950s, the government tried to regulate the situation, paving the way for the setting up of the NDAF. From its inception in 1962, this body has directed government help and money to people who have suffered from geomorphological and other natural hazards.

In the 1970s, the need for better rules and regulations regarding compensation led to government and insurance companies setting up the NPP. From 1 January 1980, the property of every citizen (such as houses and house contents) insured against fire is also insured automatically against natural hazards. The premium for this is 0.01 per cent of the fire-insurance value. Cars and boats are not, however, insured in this way, nor are forests or agricultural land.

The NPP pays out the insurance amount directly; the NDAF only pays when the rebuilding or restoration has been completed. The NDAF also finances construction of preventive works; it surveys hazard-prone areas and attempts to secure buildings, roads, railways, power lines and agricultural land against natural hazards. The financial contribution from the NDAF for preventive measures is given after surveys have indicated the best course of action. During the years 1962-90, construction of preventive works cost the NDAF 104 million NOK, representing 60 per cent of the total cost; the remainder was paid by the people involved or the municipality. Protection against avalanches cost 41 per cent of the total expenditure on preventive works; rock slides 26 per cent, debris and clay slides 21 per cent, and floods 10 per cent. Only 2 per cent was spent on measures to mitigate storm or storm-surge damage because of the great difficulties in predicting where storms will occur and the level of their severity, as well as the enormous length of coastline potentially at risk. The relatively low level of expenditure on flood prevention is because another body contributes in this field, namely the Department of River Maintenance of the Norwegian Water Resources and Energy Administration (NVE).

In the early years after the NDAF was set up in 1962, the survey and mapping of hazard-prone areas, as well as the evaluation and planning of preventive works, was done by the NDAF itself. As the case load and amount of work grew, it became necessary to call on the Norwegian Geotechnical Institute (NGI) [Environment, Avalanches and Dams Division] and on the Department of River Maintenance of the NVE. The main task of the latter even before 1939 had been the construction of protective works against river bank erosion and flooding. Today the Department takes care of the survey, evaluation and planning of these control works, and in some cases is responsible for their construction. By the end of 1988, projects under construction amounted to 100 million NOK. The counties of Hedmark (18 million NOK), Sør-Trøndelag (13 million NOK) and Sogn og Fjordane (10 million NOK) stand at the head of the expenditure list, with Aust Agder (300 000 NOK) at the bottom. Further construction works to the value of 140 million NOK have already been approved, and there are also applications totalling 335 million NOK awaiting approval.

From the late 1960s, the mapping of avalanche-risk areas was included in the work of the NGI, whose Environment, Avalanches and Dams Division has now taken over responsibility for all mass movements. The Division began preliminary work in 1976 on mapping areas susceptible to hazardous mass movement, and in the early 1980s developed a method of mapping hazard zones. After the great clay slide at Rissa in 1978, a new attitude towards this particular hazard resulted in more government money becoming available for the mapping of quick clay areas. The Division has also set up a Research Station in a mountain valley near Stryn to study avalanches; and during the 1980s has used measuring devices to keep rock movement at Stranda, Aurland, Vik, Hjelmeland, Høyanger, Leikanger and Stryn under observation. In addition to this research amd measurement programme, the Division gives advice in cases of acute danger from mass movement and as regards evacuation. Temporary works to provide security for people and property, as well as actual first aid at the scene of a disaster, are also part of its work.

Besides the work done by the branches of the NGI and NVE to prevent hazard damage, there has developed through the years a set of rules and regulations encompassed in a Building Code. This, together with the advice given by the NVE and NGI, and the latter's hazard zone maps, strongly guide the work of municipalities in designing their own Master Plans. The latter provide guidelines for differential land uses in an area, and rule out certain areas as dangerous, both as regards specific hazards and specific land uses. The work of the NVE and NGI, together with the municipal Master Plans, include both an assessment of the physical processes involved and the risks of geomorphological disaster and damage. Following on from this, there is an overall evaluation of the consequences of man's interaction and a cost-benefit analysis.

8. Conclusion

At the end of the last glaciation, the most impressive geomorphological extreme event must have been the rapid drainage of the glacier-dammed lake in northern Østerdalen. A lake 140km in length was held up by the remnants of the inland ice and drained south through the Jutulhugget canyon between 9500 and 8500 BP. The water escaped down Østerdalen into the Romerike fjord. Before the immigration of people, the event was no hazard, other than erosion "damage" which nature healed in the following centuries.

On the basis of deaths caused, property lost or damaged the clay slides of Gauldalen and Verdalen, together with the rock slides and flood waves of Loen and Tafjord, must be counted as the main disasters resulting from geomorphological hazards in Norway. As has been shown, however, storms and floods have the largest overall impact on the natural environment and society in terms of extent and cost.

The distribution pattern of the different types of hazard shows clearly that the western and northern parts of the country are more vulnerable. The coastal zone is subjected to storms, and, just inland, the zone of deep valleys with the threat of various types of mass movement is in addition liable to experience flooding, fluvial erosion and sedimentation.

Apart from the distribution of people, the prerequisites of strong relief, unconsolidated debris lying on steep slopes, and the storms and high precipitation brought by North Atlantic cyclonic weather systems, clearly guide the distribution of hazards in Norway. In the Trøndelag area and the south-east of the country, the existence of the post-glacial marine clay is the prerequisite for clay slides. The clay slide disasters clearly show how man can act as a triggering agent; and he may well be a supplementary factor in some special cases, such as the situation in which bank protection works along one part of a river increase the risk of erosion farther downstream.

The tremendous storm in the first days of 1992 on the coast of Møre og Romsdal showed that, on the whole, the immediate post-disaster aid systems worked well, though some aspects could have been improved. In particular, restoration of electric power was not given sufficiently high priority, which resulted in unexpected and severe problems for both the people and animal husbandry. The storm also put a question mark over the Building Code since some newly-built houses suffered severely. This may have been partly a result of houses being built in the "wrong" places, as no storm with such high wind speeds had occurred for many years: and people were not used to regarding a place as being unsafe owing just to high winds. Hazard-zone maps providing information to local authorities about risks from hazards have not included the possibility of storm damage, as the risks are hard to quantify and locate on maps. But the storm at the start of 1992 showed the vulnerability of society when things we have been used to do not function, and how small people are against the forces of nature.

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POLAND

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1. Introduction

Poland exhibits a diversity of relief ranging from lowlands in the north, extending from the coast of the Baltic Sea to the gradually rising edge of the uplands in southern Poland. Farther south still, and close to the frontier with Czechia and Slovakia, more restricted areas of alpine relief in the Tatra rise to a maximum height of 2655m. The lowlands of north and central Poland are mantled throughout by Quaternary deposits, in some places of considerable thickness and, with other older strata beneath, concealing the platform basement. Relatively stable tectonically, the presence of this ancient cratonic foundation, an extension westwards of the Russian Platform, effectively protects the area from significant earthquake (or volcanic) activity. In the west, the northern Polish lowland merges with the north German lowland, and the sub-surface basement includes segments of Caledonian and Hercynian cratonization. Only in the south of Poland do more recent (and still active) tectonics of the Alpine belt intrude.

About 91 per cent of the territory of Poland lies below 300m. Not only is it tectonically relatively stable, but it also escapes from the worst of the disturbed weather systems of Atlantic Europe; storms and intense precipitation are comparatively rare. One might conclude from this that this country of 312 500km^2, with its population of more than 38 million, is in terms of geomorphological hazards one of the safest in Europe, but a closer examination shows that, locally and from time to time, both natural and human-induced processes can cause serious problems.

2. The flood hazard

Because such a large part of Poland consists of lowland traversed by major rivers with very variable regimes, one of the chief hazards is the risk of flooding. Protection against flooding has a long history, but it is only in comparatively recent times that the technology for defence against floods on big rivers has been available. The first records of local embankments for flood protection in Poland date from the 13th century, though doubtless some earlier attempts at protection had been made. Fig.15.1 shows the recording of the high floods of 1570, 1584, 1719 and 1891 on the walls of the old city in Toruń, on the lower Vistula. It is in the later part of the 19th century, however, that there began a period of intense activity to regulate the rivers. By 1985, 370 rivers in Poland had been completely or partly embanked along a total length of 9208km. Of these, only about 40 - 50 per cent are designed to protect against the 100-year flood, and at least 1500km are in need of modernisation. According to hydrological engineers, another 5400km of embankment are needed, which could protect 4500km^2 and some 400 000 people.

The principal methods of flood mitigation are river regulation, construction of storage reservoirs and embankments, and catchment modifications (biological measures, land-use changes and so on).

Fig.15.1 High-water marks on the walls of the old city in Toruń (photo M. Grześ)

Stage and timing are the most critical elements in flood analysis. On most of the big rivers in Poland, floods in the winter season (November-April) reach higher levels than those of summer (May-October). For example, at the Korzeniewo gauge on the lower Vistula, the maximum winter water level is 1106cm (recorded in March 1877), while the maximum summer water level is 876cm (in June 1962), a difference of 2.3m. The differences between high and low water in winter are also greater than in summer, and these differences are related to the ice-jam phenomenon (Grześ, 1991; see below). As a consequence, embankments in Poland are divided into two types - those built to contain the winter flood and those that will contain the summer floods but may be overtopped in winter. In both cases, calculations are based not only on flood-level probability but also on economic considerations. Table 15.1 shows the guidelines, cities clearly requiring the best level of protection, even against the 1000-year flood, whereas it is admissible for poor agricultural land to be flooded once every 10 years. Eighty per cent of all floods in Poland are of the winter types, and about a half of these occur in March; 20 per cent are summer floods with a maximum in July (Mikulski, 1963).

Table 15.1. Critical data for summer and winter floods (Dębski, 1978)

Types of area to be protected	Permissible recurrence interval (years)	Probability (per cent)
(a) summer embankments		
Good arable land	25-50	2-4
Poor arable land	10-25	4-10
Meadows	5-10	10-20
(b) winter embankments		
Cities	500-1000	0.1-0.2
Industrial towns	200	0.5
Villages	100	1.0
Cultivated areas:		
of highest value	50	2
of medium value	25	4
of low value	10	10

2.1. Types of flood

There are three basic causes of river flooding in Poland: heavy rainfall, snow thaw and ice jams. Fig.15.2 shows their incidence, and also that of coastal flooding (see section 5).

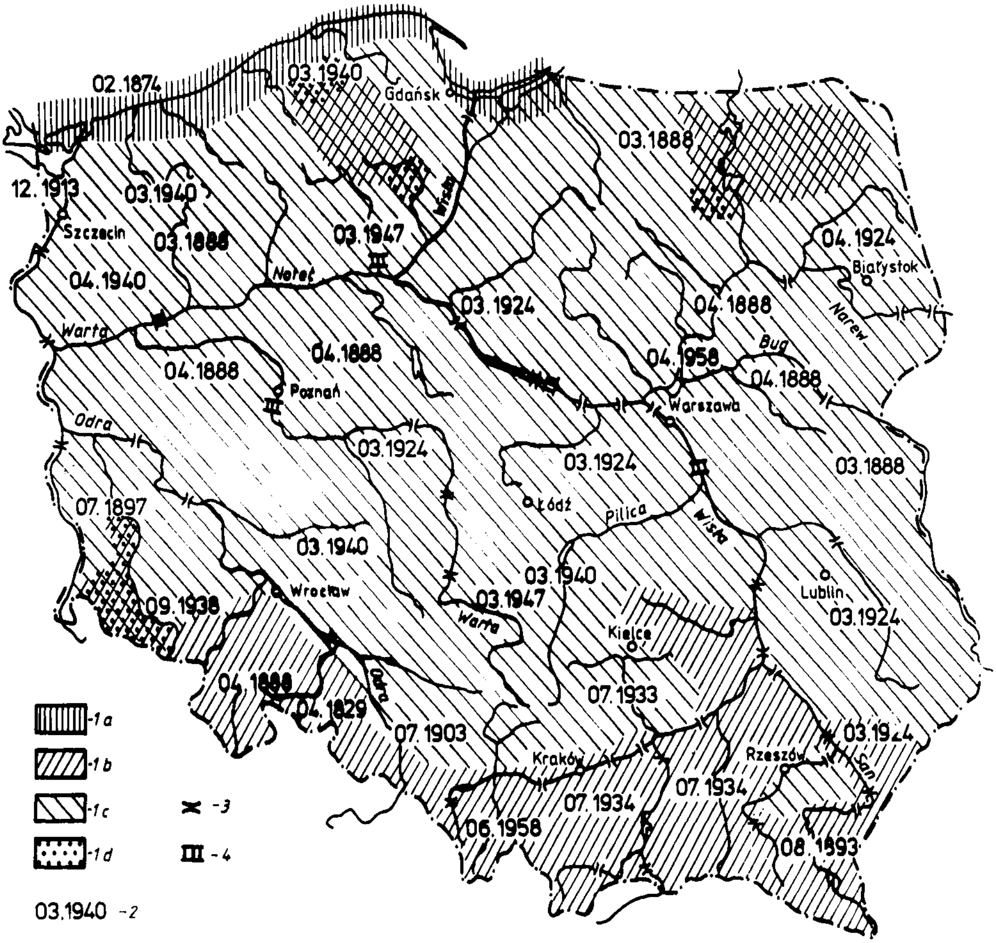

Fig.15.2. Map showing distribution, incidence and types of flood in Poland. 1a - November-December (storm surges); 1b - July-August (summer rainfall floods); 1c - March-April (snowmelt floods); 1d - October-November (autumn rainfall floods); 2 - dates of catastrophic floods; 3 - location of spring ice jams; 4 - location of winter ice jams. Adapted from Mikulski (1963)

Heavy rainfall. These depend very much on the duration, extent and character of the rainfall. The worst are related to torrential storms in mountainous areas and occur mainly in the period May to September, the most intense being in July and August at harvest time. Floods related to frontal rainfall affect vast areas of the country. The biggest such events happened in 1934, 1960, 1970 and 1980. The floods of 1980 affected the whole country. Table 15.2 gives some data for the levels of damage caused by rainfall-related floods.

Table 15.2. The range and scale of damage resulting from rainfall-related floods

Types of damage and loss	Units	1934	1960	1970	1980
Flooded area	ha	250 000	352 710	156 000	1 745 000
Damaged buildings	number	22 000	27 000	23 000	26 000
Damaged bridges	"	102	1 207	1 400	500
Damaged roads	km	100	596	751	1 800
Damaged embankments	km	100	330	100	65
Number evacuated	persons	100	65 600	35 000	20 000
Death toll	"	55	1	6	-

Fig.15.3 Masses of piled-up ice floes from the Vistula river at Wola Brwileńska on the road from Włocławek to Płock. Photo taken after the elimination of the ice jam of January 1982 (photo M.Grześ).

Snowmelt. Floods of this type depend on the thickness of snow cover, weather conditions during thaw and the state of the ground (frozen or not). Snowmelt floods are often intensified by rainfall and can extend over huge areas. One of the biggest was in March 1924, when the discharge of the Vistula at its mouth rose to 9550m^3/s, and in April 1940 the figure was 8920m^3/s. Smaller catchments in the Polish lowlands also suffer: for example, the snowmelt floods of 1958 and 1979 in the Narew basin were each the equivalent of 200-300mm of rainfall.

Floods owing to ice jams may occur during the formation and break-up of the ice cover on rivers. They are extremely difficult to predict and can cause great damage to river regulation and other construction works (Grześ, 1991). The biggest recent flood of this type took place on the Vistula river in January 1982 (Fig.15.3 and 15.4), on the

Fig.15.4. Destruction of Vistula dyke by the catastrophic ice-jam flood of January 1982. The photo was taken in March showing repairs under way (photo M.Grześ).

Włocławek Reservoir, when more than 100km^2 of the valley were inundated.

The exact mechanism by which the river becomes blocked or partially blocked is complex; essentially it involves reduction of the wetted perimeter of the channel, and certain channel morphologies are more favourable than others to ice-jam formation. The main locations predisposed to ice jamming are marked on Fig.15.2. Part of the complexity of the situation results from the position of Poland on the boundary between maritime and continental climates, so that individual winters may have two or more cycles of complete river freezing. On the big rivers such as the Vistula, which flow from south to north across the country, the break-up of the ice cover starts earlier in the south and is linked to the snowmelt flood. The flood travels downstream to encounter a barrier of river ice, which begins to break, but the ice floes then pile up over each other to create a blockage (Fig.15.5).

Fig.15.5. Surface of the ice jam on the Vistula at Płock, February 1987 (photo M.Grześ)

2.2 Flood losses

About 7 per cent of Poland (some 20 000km^2) is under threat of flooding. This area includes 16 000km^2 of fertile agricultural land, a population of some 1.5 million, and about 1500 industrial plants. 65 per cent of all the losses arise in the Vistula basin, and most of the remainder are associated with the Odra (Oder) basin. As Table 15.2 shows, there is a tendency for losses to increase year by year; Table 15.3 shows the losses indexed in relation to the Gross Domestic Product (Grochulski and Żelazo, 1988).

Agriculture suffers the most. Losses between 1976 and 1986 amounted on average to 66 per cent of total losses. The worst are related to rainfall floods (Table 15.3); in 1980, floods of this type caused losses to exceed 1 per cent of GDP, and 88 per cent fell on agriculture. In that year, 1745km^2 were flooded and 1800km of roads were damaged.

Complete flood protection is not possible; the level of protection is a matter of technology and cost. Every flood protection system has its limits, as is readily demonstrated in the case of the Narew and Bug rivers (Fig.15.2). The Bug has neither large enough embankments nor sufficient storage reservoirs, and during the thaw in 1979, flooding caused severe damage in its catchment. A similar situation arose in the Narew basin in 1958, when Pultusk was flooded because of lack of embankments, and in 1979 the situation was repeated when the new embankments built to protect Pultusk broke.

Paradoxical situations arise when flood losses are greater after embankment construction than before, largely because the presence of such structures gives a misplaced sense of security leading to the urbanisation and/or intensive cultivation of land that is at risk if the structures then fail. In such a situation, breaking of an embankment causes more damage than if it had never been built. Land-use zoning and re-scaling of insurance premiums are therefore imperative.

2.3 Floods on the Vistula

The River Vistula (Fig.15.6), with a length of over 1000km, drains a catchment of nearly 200 000km^2 of which 87 per cent lies in Poland. The average basin rainfall is about 600mm/year. Two flood periods can be distinguished: in March-April owing to snowmelt, characterised by high and prolonged discharge peaks, and summer rainfall-induced floods from late June to late July. Ice cover on the river lasts roughly 6-8 weeks. Transport of solid material is estimated at 800 000t/year (Manthey, 1981). On the upper Vistula, flood levels can be 5-6m above low-water level; on the middle and lower Vistula 7-9m, and at Tczew over 10m.

As already noted, many of the winter floods are caused by ice jams. Two types of these can be identified: the first forms during the freeze-up period (winter jams) and the second during the ice break-up period (spring). The behaviour of the river in the spring type is complicated by the fact that this time of the year tends to coincide with snowmelt floods. It was a series of disastrous ice-jam floods earlier this century that spurred on progress in river regulation works. In the early stages of this regulation programme, ice-jams became more frequent, but since the river has adjusted to the new conditions, there

Table 15.3. Types of flood and flood losses, 1957-86

Year	Months												I(%)	Apportionment of losses between the catchments of the:	
														Odra	Vistula
	J	F	M	A	M	J	J	A	S	O	N	D		(per cent)	
1957	-	-	-	-	-	-	-	-	-	-	-	-		100	-
1958	-	-	1	1	-	-	2	-	-	-	-	-	0.332	26	74
1959	-	-	-	-	-	-	-	-	-	-	-	-	0.022	28	72
1960	-	-	-	-	-	-	2	-	-	-	-	-	0.651	7	93
1961	-	-	-	-	-	-	-	-	-	-	-	-	0.016	100	-
1962	-	-	-	-	2	2	-	-	-	-	-	-	0.404	44	56
1963	-	-	-	-	-	-	-	-	-	-	-	-	0.027	21	79
1964	-	-	1	-	-	-	-	2	-	-	-	-	0.150	32	68
1965	-	-	1	1	2	2	-	-	-	-	-	-	0.247	68	32
1966	-	-	-	-	-	-	-	-	-	-	-	-	0.157	40	60
1967	-	1	1	-	-	-	-	1	-	-	-	-	0.057	18	82
1968	1	1	-	-	2	-	-	-	-	-	-	-	0.103	53	47
1969	-	-	-	-	-	-	-	-	-	-	-	-	0.040	17	83
1970	-	-	1	1	-	-	2	-	-	-	-	-	0.535	5	95
1971	1	4	1	1	-	2	2	-	-	-	-	-	0.076	76	24
1972	-	-	-	-	2	-	2	2	-	-	-	-	0.194	24	76
1973	-	-	-	-	-	-	2	-	-	-	-	-	0.128	1	99
1974	1	-	-	-	-	2	2	-	-	2	-	2	0.163	5	95
1975	-	-	-	-	-	-	2	-	-	-	-	-	0.027	17	83
1976	4	-	-	-	-	-	-	-	-	-	-	-	0.004	37	63
1977	-	-	4	-	-	-	2	-	-	-	-	-	0.503	87	13
1978	-	-	-	-	-	-	-	-	-	-	-	-	0.011	20	80
1979	-	-	3	3	-	-	-	-	-	-	-	-	0.352	48	52
1980	-	-	-	-	-	2	2	-	-	-	-	-	1.041	25	75
1981	-	-	-	-	-	2	2	2	-	-	-	-	0.128	83	17
1982	6	6	-	-	-	-	-	-	-	-	-	-	0.184	25	75
1983	5	-	-	-	-	-	-	-	-	-	-	-	0.087	11	89
1984	-	-	-	-	-	-	-	-	-	-	-	-	0.009	12	88
1985	-	-	-	-	2	-	2	-	2	-	-	-	0.268	68	32
1986	-	-	-	-	-	-	2	2	2	-	-	-		38	62

Key: I = Index of losses, per cent of GDP
Flood types: 1 - snowmelt; 2 - heavy rainfall; 3 - snowmelt and ice jam; 4 - snowmelt and rainfall; 5 - coastal storm surge; 6 - ice jam

Fig.15.6. The Vistula upstream from Plock, summer low water (photo M.Grześ)

has been an improvement, though there is still a certain risk of ice-jam floods. The use of ice-breakers on the river, which themselves demanded improvements in navigation, remains the basic method of fighting ice jams. On the lower Vistula (Fig.15.7), the height of the ice-jam dams does not usually exceed 2-3m; occasionally it reaches 4m, as at Chelmno in March 1937. The biggest ice-jam flood on the Vistula took place in the Tczew region in 1855; about 440km^2 of valley floor were then inundated. As the ice jam begins to break the speed of flow increases dramatically, up to 3-4m/s, and the rapidly moving ice floes can cause severe damage to the bed and sides of the channel.

During this century, thirty major floods have occurred in the Vistula basin. The most serious were in 1903, 1924, 1927, 1934, 1938, 1947, 1960, 1962, 1970, 1972, 1979, 1980, 1982 and 1983. On average, there has been one major flood every 3 years (*Zarys monografii powodzi w Polsce, 1988*): a comparative figure for the Odra catchment is 5 years. Although there are long records of the history of flooding available, frequency analysis is difficult and subject to large errors. In the first place, in the past only catastrophic floods tended to be recorded, and even then only in areas near to big cities (Grześ, 1991). Secondly, there have been considerable changes in river regime brought about by regulation works, deforestation, land reclamation and other changes in land use. Therefore historical events are not strictly comparable with later events, and should not be used for estimating whether there has been any increase or decrease in flood risk.

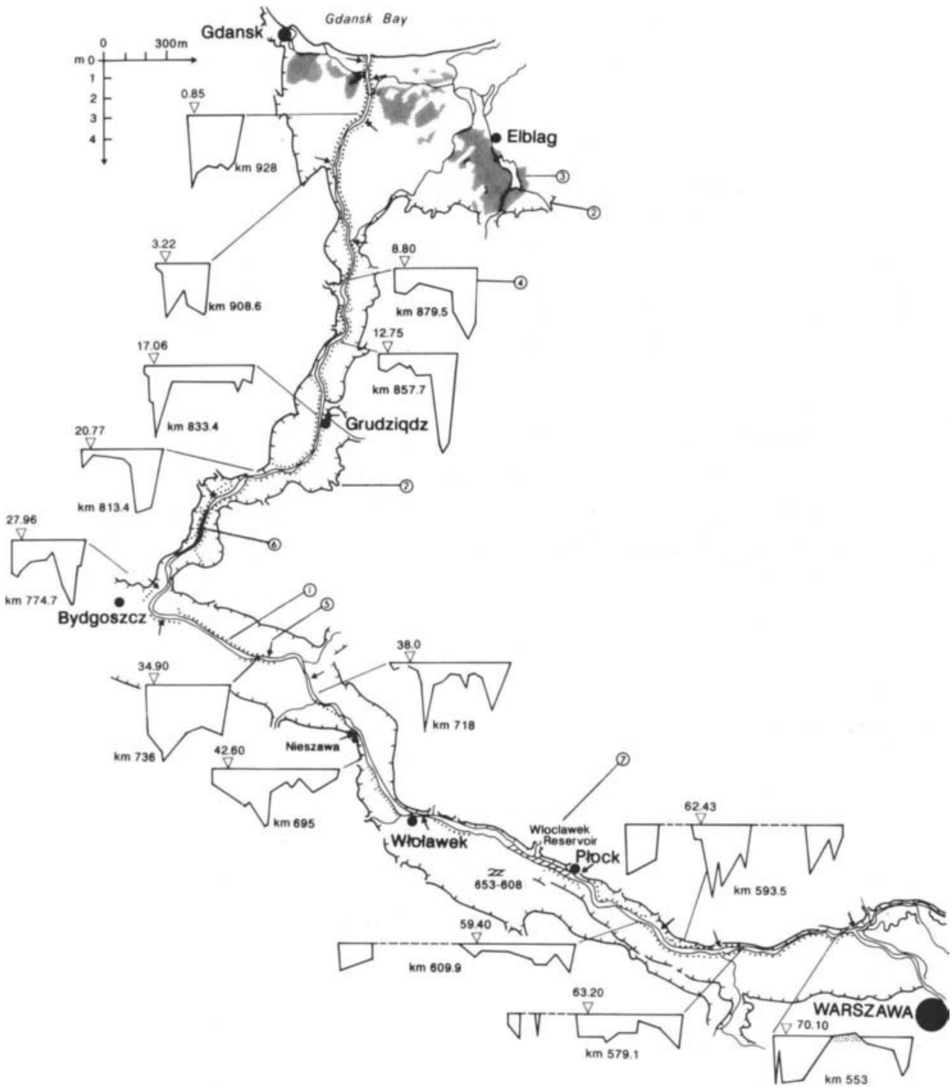

Fig.15.7. Map of the lower Vistula river. Numbers in small circles on the map refer as follows: 1 - embankments; 2 - edge of valley; 3 - depressed areas (shaded); 4 - channel cross-sections; 5 - gauging stations; 6 - reaches liable to ice jams; 7 - Wloclawek reservoir

3. Mass movements

Figure 15.8 illustrates the paradox that mass movements are both concentrated in certain localities or regions and widely dispersed across the territory. This is true both of the more spectacular and catastrophic landslides and of the less obvious and longer-acting processes such as soil creep and slope wash which can be monitored only by

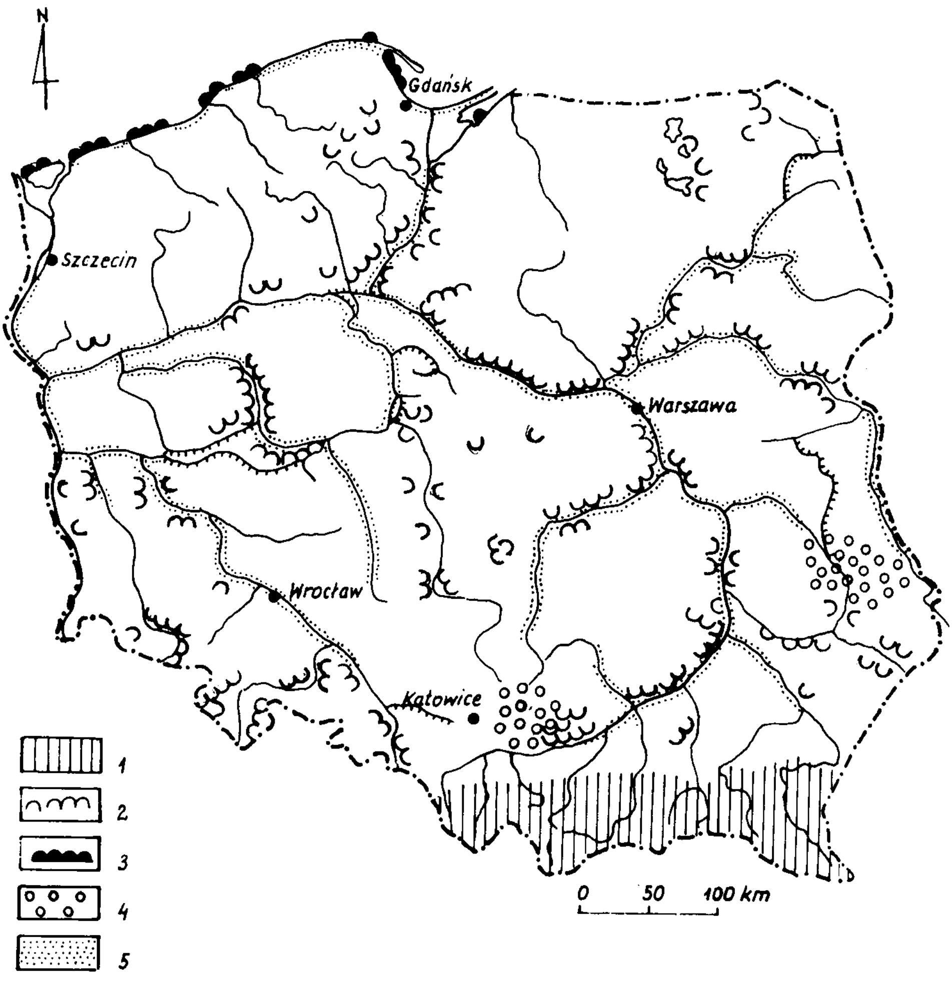

Fig.15.8. Location of some geomorphological hazards in Poland excluding floods. 1. Frequent landslides; 2. Separate major landslides; 3. Mass movements on coastal cliffs; 4. Karst subsidence; 5. Natural aeolian processes

careful measurement. Major landslides are most characteristic of the Carpathian mountains in the south-east of Poland (Fig.15.9), but as Figure 15.8 shows, can be found in many other areas too.

The location of areas at risk from major landslides is controlled by two main factors: the presence of slopes with a favourable geological structure, and high levels of precipitation. Both of these conditions are fulfilled in the case of the flysch Carpathians, consisting of interbedded shales and sandstones, deeply dissected by numerous valleys. The annual precipitation here reaches 800-1100mm, sometimes concentrated in rainstorms. On Figure 15.8, the extent of this area (marked with vertical shading) is necessarily generalised: in reality, the hazard is more potential than actual. Michalik (1970) has estimated that only 672km^2, or 4 per cent of the area of the Carpathians within Poland, has been in the past, or is being at present, endangered by landslides or other forms of mass movement.

The temporal incidence of mass movements is strongly correlated with climate. During wet years, or soon after, an increasing number of fresh or revitalised landslides is reported. According to Ziętara (1968), the recurrence interval of wet years in the Car-

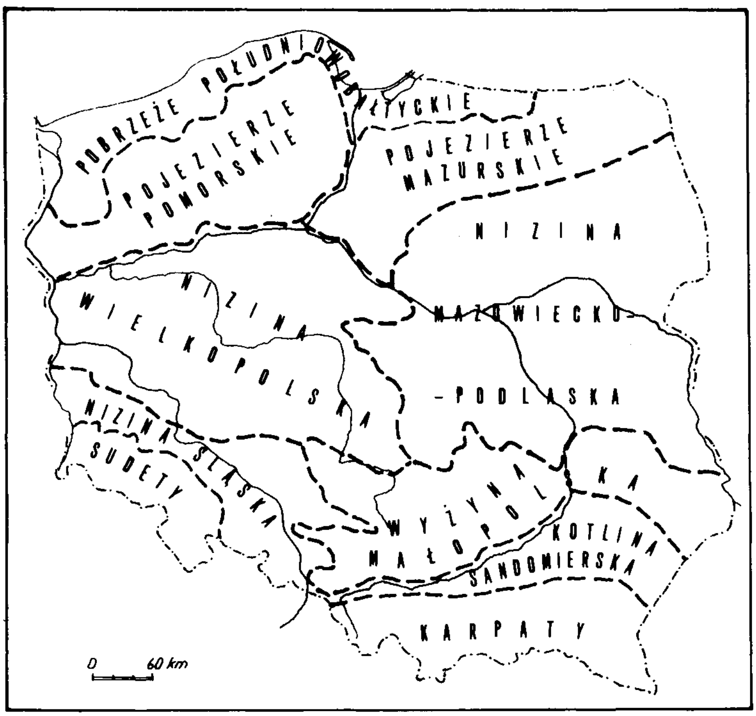

Fig.15.9. Main physiographic units in Poland

Fig.15.10. Mass movements on the bank of the Włocławek reservoir at Dobrzyn, triggered by the raised water level (photo M.Grześ)

pathians is 30-32 years. As well as meteorological causes acting as the final trigger for slope failure, the effect of earthquakes, possibly far away, should not be overlooked. In 1957, for example, a landslide with a surface area of 20 000m^2 at Lipownica in the eastern Carpathians was released by an earthquake whose epicentre was situated 1100km away in Thessaly, Greece (Gerlach *et al.*, 1958).

Sooner or later, all landslide tongues reach the floors of the valleys, where they are subject to fluvial erosion. Their impact on the development of the Carpathian relief seems to be quite significant. Starkel (1962) estimated, for instance, that during the Holocene, about 500 000m^3 of material has been removed by mass movements from each 1km^2 of the flysch Carpathians, which equates to an average rate of about 50m^3/km^2/year. At present, the figure is about three times higher, basically owing to human interference with the natural systems.

In the Sudeten mountains of south-west Poland (Fig.15.9), mass movements are not so frequent or serious, largely because of different geological conditions. Throughout a long geological history, the Sudeten mountains have passed through all the main European orogenic phases, as a result of which the structure now consists of a mosaic of resistant igneous and metamorphic rocks. Although dissected by numerous faults, the lithological conditions for major mass movements are lacking.

As already remarked, mass movements are by no means confined to the south of Poland, but can occur in any area where the geology is favourable and the relief is characterised by slopes of sufficient height and gradient. They are thus most frequent in the area of the Pleistocene plateaus in northern Poland, along deeply incised valleys (Fig.15.10), and especially on the Baltic coastal cliffs of glacial deposits where cliff falls and slides are frequently reported (Fig.15.8). Even apparently stable slopes of fossil cliffs or valleys with forest 150-200 years old can be destabilised during wet years. Such events were observed, for instance, in 1981 along the coastal promenade between Sopot and Gdynia. As a result of three landslides on fossil cliffs in the space of 1.5km, the promenade has been partly destroyed.

4. Coastal cliff and dune erosion

Out of a total coastal length of 500km, high steep cliffs characterise only 45km, the remainder consisting of flat coastline with sandy beaches and coastal dunes. Cliffs only exist in those places where the northern margins of the Pleistocene plateaus reach the coast (Fig.15.11). Cliff heights vary greatly depending on the local topographic situation,

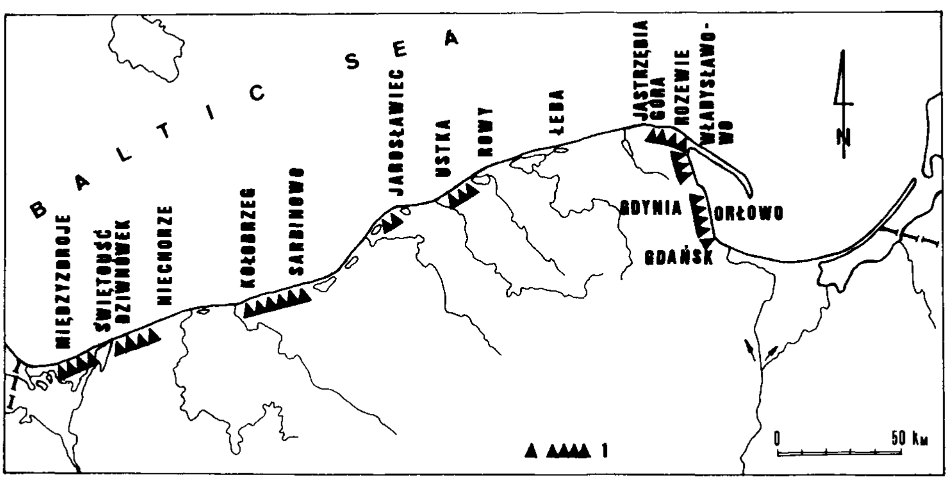

Fig.15.11. Location of coastal cliffs in northern Poland (Subotowicz, 1982)

but are mostly in the range 5-30m. Where subject to wave attack, the cliffs expose in their internal structure a great variety of glacial and glacifluvial materials, sometimes interbedded with Tertiary deposits packed in as glacio-tectonic elements. All these materials are of low resistance: Table 15.4 gives data on rates of cliff retreat.

Table 15.4. Some rates of retreat for coastal cliffs in northern Poland (Subotowicz, 1982)

Locality	Period of measurement	Amount of retreat (m)	Average rate cm/year
Wolin	1886-1961	0.26-1.33	0.35-1.77
Wolin	1695-1924	0.90	0.39
Trzesacz	1842-1908	0.31-0.41	0.47-0.62
Niechorze	1842-1892	0.10-0.71	0.20-1.42
Ustronie M.	1882-1923	0.45	1.10
Ustronie M.	1961-1971	0.10-3.10	1.00-31.0
Sarbinowo	1783-1924	0.70-1.90	0.50-1.35
Jaroslawiec	1842-1922	0.41-0.60	0.51-0.75
Jaroslawiec	1961-1971	1.40	14.0
Ustka	1862-1938	2.00	2.63
Ustka	1960-1978	1.00-2.30	5.56-12.78
Rozewie	1837-1959	2.35	1.93
Orłowo	1837-1959	0.80	0.66
Orłowo (Fig.15.12)	1963-1975	1.00	8.33

A good example of coastal cliff erosion is at Trzęsacz, near to Niechorze (Fig.15.11). Historical documents show that the church in Trzęsacz was built in the centre of the village in the year 1250. At that time, the church was probably about 1500m from the cliff top. By 1750, this distance had been reduced to 58m, by 1855 to 5.5m and in 1868, only a metre separated the church from disaster. The church was closed in 1874, and Figure 15.13 charts subsequent events up to 1966. Historical evidence combined with modern precise measurements make it possible to fix the rate of cliff retreat here with great accuracy.

Cliff retreat which represents a serious hazard for buildings near the cliff top is accelerated by the numerous springs of groundwater which promote mass movements of all kinds (Subotowicz, 1982). The erosion is strongly episodic; most cliff-foot abrasion takes place during periods of stormy weather in late autumn and early winter, and also in early spring. Schöneich (1964) has also claimed that neotectonic movements in the deep substratum help to destabilise the cliffs in some places and thus affect erosion rates.

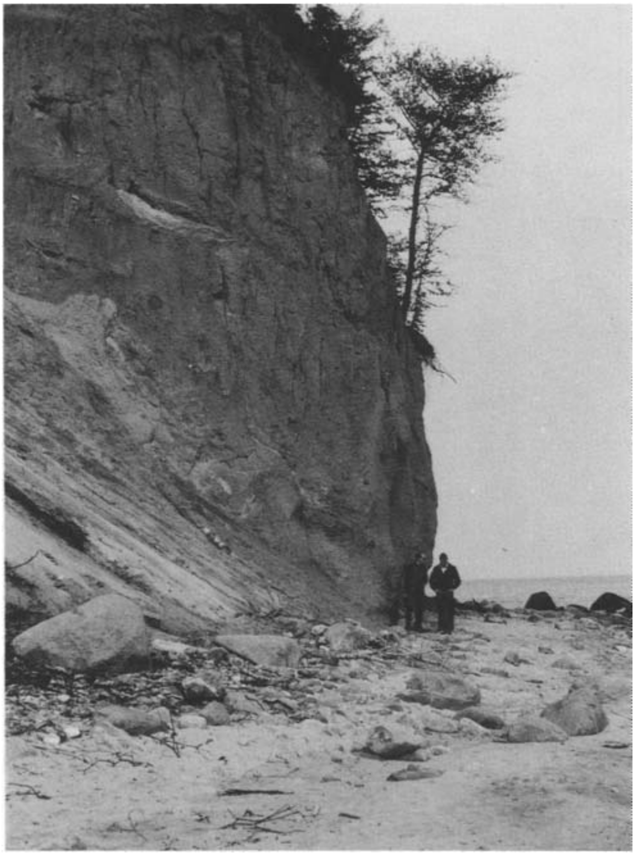

Fig.15.12. Cliffs in Pleistocene deposits at Orłowo, northern Poland (photo C.Embleton)

Dune erosion is another aspect of potentially hazardous coastal change, and is also episodic in character, linked with exceptional winter storms. The last two major occurrences, in 1993 and 1982, were both in January. In 1982, one of the authors (A.H.Rachocki) observed and recorded the effects of a severe storm on the Hel peninsula. For a distance of about 15km, the dunes were undercut producing a low continuous cliff 3-8m in height. At its narrowest point, the width of the Hel peninsula does not exceed 300m, and Hel was then in serious danger of being cut off. A similar situation recurred in 1993. The violence of the storms can be so great that even beaches 40m wide do not prevent the outer dunes being undercut. At a rough estimate, the total volume of dune sand removed from the Hel peninsula by waves in a single storm in 1982 was no less than 80 000m^3. Bearing in mind that 90 per cent of the Polish coast is flat, with sandy beaches and dunes, the scale of the problem can be appreciated.

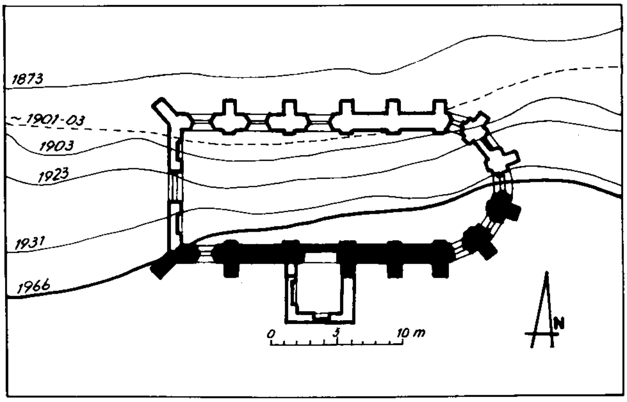

Fig.15.13. Cliff retreat at Trzęsacz. Walls still standing are shown in black.

5. Coastal flooding

Another geomorphological hazard closely related to on-shore storms of Beaufort 7-8 or more and the consequent set-up of the sea-level surface is coastal flooding, seen in the periodic inundation of coastal plains and deltas. In severe storms, the water set-up can exceed 1m; under such circumstances, the level of groundwater beneath the coastal flatlands rises too, and in the river estuaries, reversal of flow can even be observed. In these conditions, flooding can be extensive, affecting tens or even hundreds of km^2 (Drwal, 1984). The areas under greatest threat are around the river mouths and the Zulawy depression. The coastal flooding of 1983 was one of the worst recent cases, when damage amounted to 60 per cent of all losses by natural disasters in that year.

6. Soil erosion

This is one of the most serious geomorphological hazards in Poland, the more so because of its insidious nature. According to the G.U.S.Yearbook (1992) (G.U.S. - *Glówny Urząd Statystyczny* [Main Statistical Office]), about 56 per cent of the total arable area in Poland is threatened by degradation and falling agricultural yields. The flat areas of central Poland are particularly at risk from wind erosion, as a result of several factors: a lack of sufficient precipitation, extensive deforestation and removal of windbreaks, and unsuitable agricultural practices that cause further drying of the soil and expose the soil to wind erosion at certain times of the year. Under the worst conditions of strong winds and fields bare of crops, deflation can remove the equivalent of over 10 000t/km^2/year, equivalent to a layer 1.5-2cm thick; an average rate of soil erosion by wind is 100-600t/km^2/year (Wojtanowicz, 1972, 1991).

Water erosion affects 87 400km^2: severe water erosion occurs over 11 000km^2 (G.U.S., 1992). Busek and Dominik (1990) estimate that every year about 5 million t of soil are washed out into rivers by runoff. The most favourable conditions for water erosion are to be found in the southern hilly or mountainous areas, but also in northern Poland on the slopes of the Pleistocene plateaus (Pojezierze Pomorskie, Pojezierze Mazurskie; Fig.15.9). In the flatter parts of central Poland the hazard is not very high. In the flysch Carpathians, however, soil erosion by water can give rise to removal rates of 0.5-0.9mm/year, and in the eastern part of Wyżyna Małopolska which is mantled with loess, the corresponding values rise to 5-20mm/year (Ziemnicki, 1985). It is estimated that gully erosion affects altogether no less than 21 per cent of Poland. The total length of gullies is of the order of 40 000km. The areas that are worst affected are in the south and in the north (Józefaciuk and Józefaciuk, 1980, 1991). The average density of gullies varies between 0.1 and 1.0 km/km^2, but in southern Poland the equivalent figure can rise to over 2.0, and according to Maruszczak (1958) in the loess areas of Wyżyna Lubelska, it can even exceed 10km/km^2.

7. Human-induced hazards

Modifications of the Earth's surface or sub-surface undertaken for economic purposes other than agriculture or forestry - deep mining, surface excavation, deposit of waste materials, etc. - can have far-reaching consequences for people living in the immediate vicinity, and can present types of geomorphological hazard that are just as serious as those resulting from natural processes.

7.1. Subsidence

Hazards of this type in Poland are mostly connected with deep mining of coal and other mineral ores in the industrial area of Upper Silesia. In this mining region, 60 000 ha already suffer from subsidence (Busek and Dominik, 1990). The surface becomes pitted with numerous collapse cavities or basins whose depth may even reach tens of metres. They may remain dry or may be filled with water depending on the local hydrogeological conditions. Subsidence is particularly dangerous in urban areas, causing severe damage to gas and water pipelines, electric cables and sewage disposal systems. In such areas it is common to find houses being strengthened with iron bars anchored in the walls to try to prevent further damage or collapse, but even such reinforced buildings will show cracks and joints in the walls. Another region suffering from subsidence caused by deep mining lies in south-west Poland (Fig.15.14). This is the Lower Silesian industrial region with numerous coal mines and mines for non-ferrous metals: the area near Lubin contains Poland's largest copper mines.

Local subsidence also affects some 1200ha around Tarnobrzeg where sulphur is exploited. Hot water is pumped into the sulphur-bearing layers and the resulting solution is discharged to tanks at the surface. This process causes slow continuous subsidence over

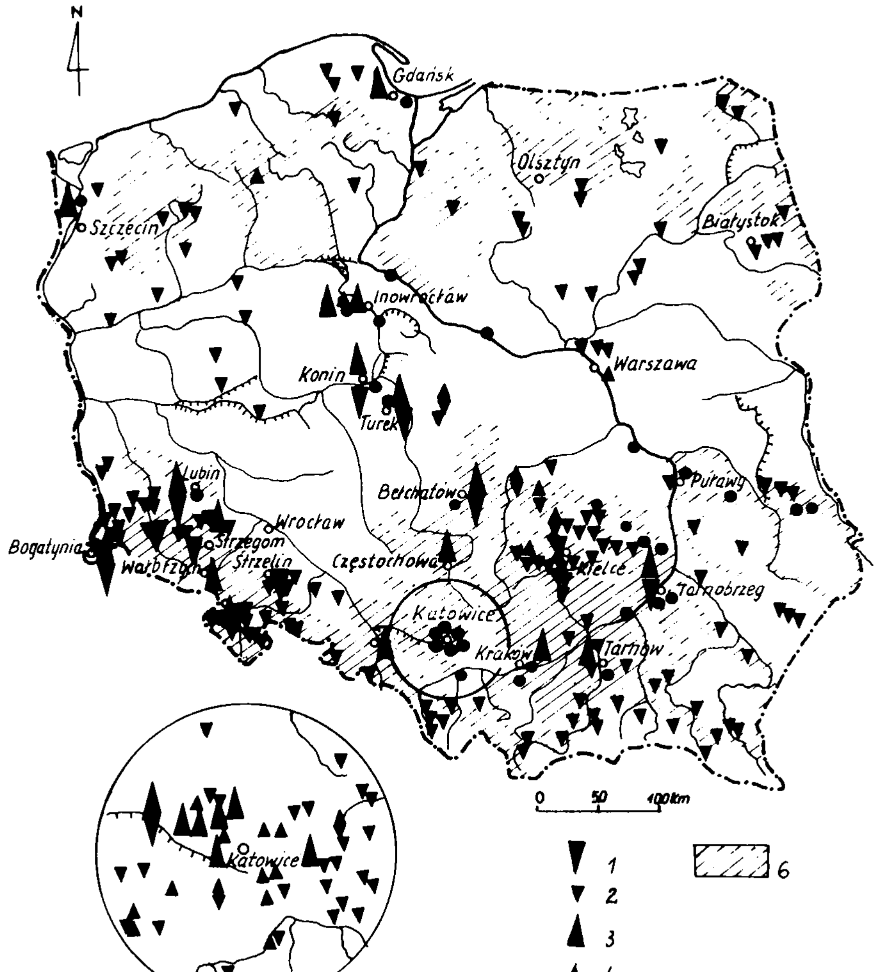

Fig.15.14. Geomorphological-type hazards induced by economic activity. 1. Opencast mines (pits) covering more than 100ha; 2. pits of less than 100ha; 3. Waste heaps covering more than 50ha; 4. waste heaps less than 50ha in area; 5. Aeolian processes active in industrialised areas (see text); 6. General distribution of areas of intensive soil erosion in Poland. The circle, lower left, shows an enlargement of the Upper Silesian industrial area.

large areas, the amount of sinking reaching 5 or even 8m; even worse, the whole area is poisoned with sulphur dust or the escape of sulphur in solution from leaky pipelines.

7.2. Industrial waste heaps

Heavy industry and especially mining produce huge amounts of waste such as spoil, ash and slag which are stored at the surface in waste heaps or cinder tips. The heights of these man-made hills can be 30-50m or even more; most are associated with coal mines and iron/steel works which are concentrated in the Upper Silesian and Lower Silesian industrial regions. The following data give some idea of the magnitude of the problem. In the year 1975, the storage of solid industrial waste amounted to an average of 2186t for every square kilometre of Poland. In 1992, the corresponding figure was 5622t. If one takes Upper Silesia alone, the amount of waste produced there in 1975 was 46 426t/km^2, and in 1991, 112 228t/km^2. The annual production of industrial waste in Poland is running at 128.3 million t; 50 per cent of this is produced in the USIA alone.

The presence of the waste heaps itself disfigures the landscape but, in addition, there are other negative effects, for example, tectonic movements in the substratum may be triggered by the load of material on the surface, dust storms and air pollution may result, and the waste heaps may spread by mass movements and surface erosion. Sudden slides of material on the waste-heap slopes represent another potential hazard.

7.3. Surface excavations

Although not so concentrated as deep coal mining, opencast mining of brown coal also presents problems. The largest pits are located near Bogatynia, Konin, Turek and Belchatów (Fig.15.14). Their depth can be as much as 200m, depending on the thickness of the overburden as well as the thickness of the brown coal seams themselves. The excavations themselves are not a particular geomorphological hazard, but the existence of these large, deep hollows causes significant changes in the groundwater levels. The pits drain vast surrounding areas: for instance, the Bełchatów pit drains an area of 1700km^2. As a result, the soil dries out more frequently, and since such pits as Turek, Konin or Bełchatów lie in an area of rainfall deficit, soil erosion by wind becomes a significant hazard.

All these pits are accompanied by huge heaps of overburden excavated from them. They can be 50-150m high, and in the case of the Turów and Konin pits, cover areas of 4000ha each. The hazards associated with them are the same as in the case of waste heaps produced by deep mining.

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PORTUGAL AND THE PORTUGUESE ATLANTIC ISLANDS

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1. Introduction

The Portuguese mainland, and in particular its southern part, is located close to the Azores-Gibraltar plate boundary and is therefore an area of significant seismic risk. A very different type of hazard is the risk from floods, associated with the Mediterranean climate and its irregular rainfall regime, which means that, on occasion, a few hours' rainfall may exceed the monthly average. Thus, from two points of view, the natural environment of the mainland is fragile and unstable. The same applies to the Azores, situated at a triple junction and subject to one of the highest rainfalls in Europe. On the other hand, the Madeira archipelago is relatively stable in terms of its seismicity, lying closer to the continent of Africa and at some distance from any plate boundary. The very steep slopes of the island of Madeira itself, however, combined with a risk of occasionally heavy rainfall, give rise to important mass movement and flash flood events.

Portugal is thus at risk from several types of potential hazard that threaten not only the lives of people but also property and the economic infrastructure. This article will deal systematically with the localisation, frequency and seriousness of potential hazards under five main headings: seismic hazards, volcanic hazards, mass movements, river flooding and coastal erosion.

2. Seismic hazards

2.1. The Portuguese mainland

Portugal is situated near the intersection of a continental margin, running roughly north-south and linked with the North Atlantic opening, and the Eurasian-African plate boundary running east-west and known as the Azores-Gibraltar fault (Fig.16.1). According to Cabral and Ribeiro (1989), the maximum compressional stress in the continental area has at present an axis directed from north-north-west to south-south-east, marking the collision between the African and Eurasian plates. In the oceanic area, the maximum stress rotates to a direction from west-north-west to east-south-east, owing perhaps to the beginning of subduction in the zone of the Gorringe and Guadalquivir submarine banks, which would imply a faster rate of African-Eurasian convergence. Cabral and Ribeiro (1989) also suggest that, to the west of the Iberian peninsula, the continental margin may be in a stage of transition from passive to active and that subduction may be starting to occur from the south to the north offshore from Portugal. If this is the case, then the north-south continental margin would be one of the main sources of seismo-tectonic activity in the Iberian peninsula, although with a lower level of activity than that of the Azores-Gibraltar plate boundary.

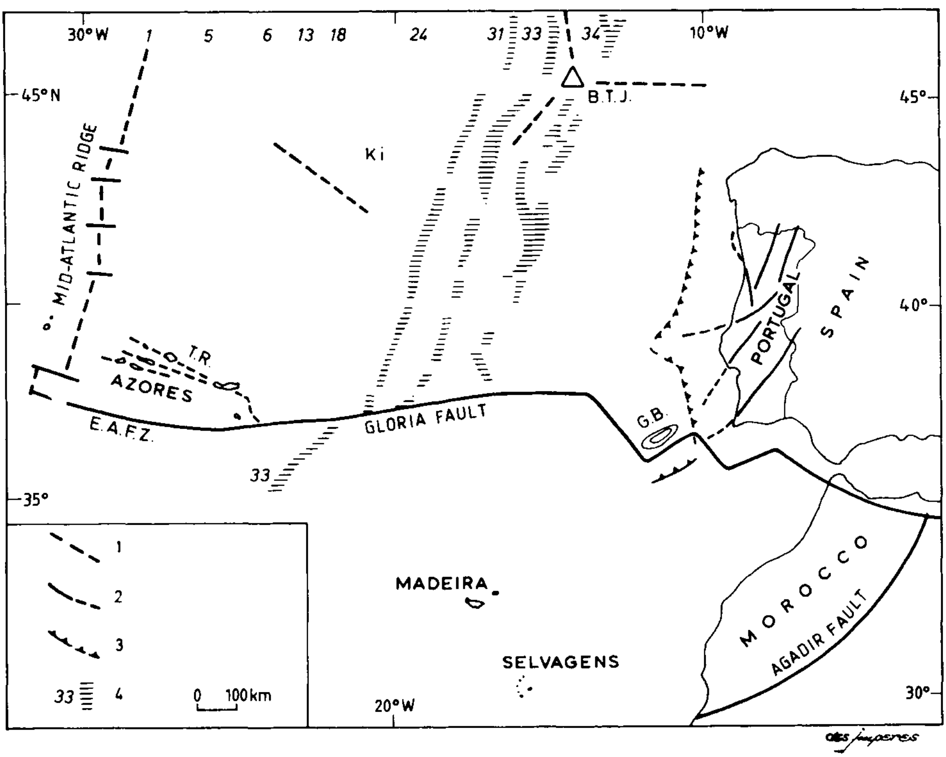

Fig.16.1. Structural framework of the Portuguese mainland and Atlantic islands (based on Verhoef *et al.*, 1986, modified by Mougenot, 1989; S.P.U.I.A.G.G., 1987; Cabral and Ribeiro, 1989). 1. Ridge; 2. Fault; 3. Subduction south of the Gorringe Bank and possible subduction of the West Iberian margin; 4. Magnetic anomalies (5 to 24 - weaker anomalies). G.B. Gorringe Bank; Ki King's Trough; B.T.J. Biscay Triple Junction (inactive); E.A.F.Z. East Azores Fracture Zone (inactive sector); T.R. Terceira Rift

The Lisbon earthquake of 1 November 1755, generally regarded as the greatest well-documented seismic event in historical times, had its focus on this plate boundary close to the Gorringe Bank. According to Machado (1966), this earthquake may have reached magnitude 9 on the Richter scale (8.75-9, according to Moreira (1984)), with an epicentral intensity of XII on the Mercalli scale. In Lisbon, the Algarve and Morocco, its intensity may have varied between IX and X. The death toll in Lisbon is estimated to have been 20 000, among a total population of barely more than 200 000. The main cause of destruction in the city was a huge fire that broke out immediately after the earthquake. Another severely affected area was the Algarve where the main towns including Faro were destroyed (Oliveira, 1977). The earthquake caused a tsunami that may have reached a height of nearly 30m at Sagres in the western Algarve (Oliveira, 1977) and was felt across the whole width of the North Atlantic. Two other important historical earthquakes located close to the epicentre of the 1755 event should be mentioned: one occurred in the year 60 or 63 BC, and the other in 1356. More recently, on 28 February 1969, another disturbance took place in the same area and may have reached M = 7.5 (Oliveira, 1986) though it only caused damage in the Algarve.

Another belt of important epicentres lies along the Tagus valley in the neighbourhood of Benavente. The earthquake of 1344 (whose exact location remains uncertain) and that of 1531 (which destroyed 150 houses in Lisbon) originated in this area, as did that of 23 April 1909 (M = 6.4-7.1). Some other earthquakes whose epicentres were located on the mainland or close to it must also be mentioned: the Setúbal seism in 1858, and two others in the Algarve in 1722 and 1856, all three with M > 6 and epicentral intensities between VIII and IX. The first shook Setúbal, Lisbon and Santarém, the other two Portimão, Faro and Tavira (Machado, 1970; Moreira, 1984). Another violent event, in this case submarine, occurred between the Azores and the mainland on 25 November 1941, M = 8.3 and epicentral intensity XI (Machado, 1970). Fortunately it was located at a considerable distance from any area of settlement, so that the shock caused no damage.

Summing up the information available from historical and instrumental records of seismicity, it may be said that, so far as the mainland and its vicinity is concerned, there are three main earthquake areas: 1) the Ribatejo, certainly associated with the Tagus fault; 2) the Algarve, along faults of east-west direction; and 3) the lower Sado valley, where the tectonic relationships have not yet been fully determined. Near the Gorringe Bank there is another important seismic zone, here a submarine one, related to the Azores-Gibraltar fault. Along the continental margin yet another seismic belt has been traced northwards from the Azores-Gibraltar fault, approximately following the meridian of 15° west (Moreira, 1982).

The highest seismic intensities have undoubtedly been recorded in the Algarve, in the coastal area of the Alentejo, in the Ribatejo and in the Lisbon area. To the north or north-east they decrease considerably. The location of continental epicentres, especially those with M < 6, does not show a close connection with the active faults identified according to geological and geomorphological criteria (Fig.16.2). Taking all the data into account, together with the distribution of human settlement in the area, a zonation of seismic risk is presented in Figure 16.3; this is necessarily different from any hazard zoning derived purely from seismic intensity and frequency.

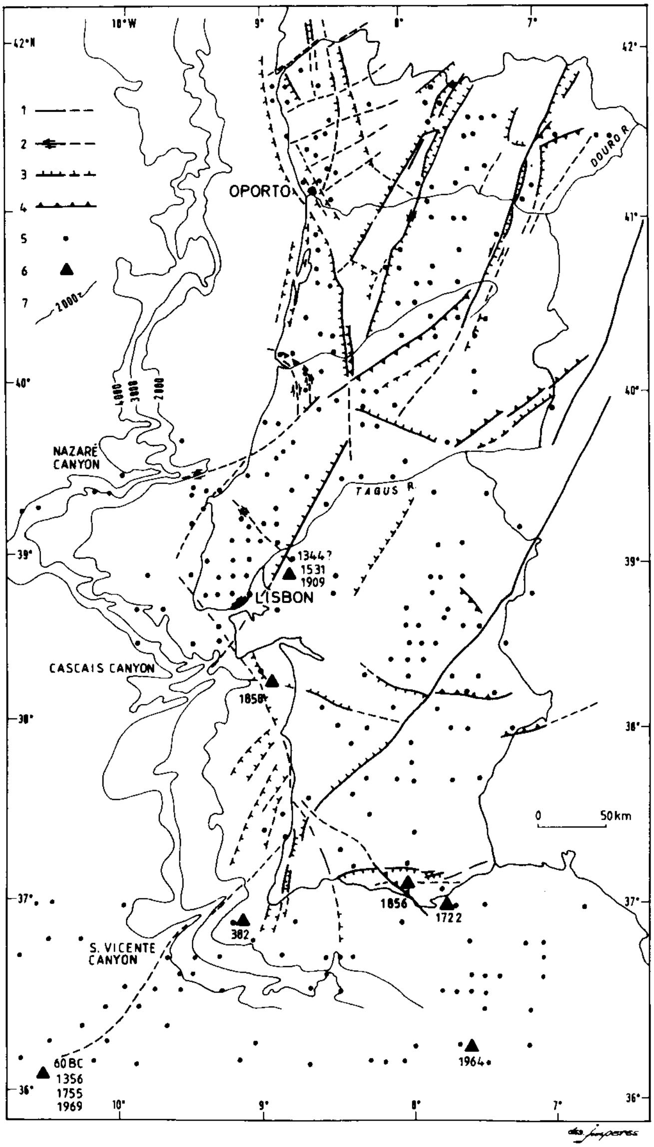

Fig.16.2. Seismotectonics of the Portuguese mainland (after Moreira, 1982 SPUIAGG, 1987; Cabral and Ribeiro, 1989, modified).

1 - Active fault in the Quaternary (broken line - hypothetical)
2 - Strike-slip fault
3 - Normal fault
4 - Reverse fault
5 - Epicentre, M < 6
6 - Epicentre, M ≥ 6
7 - Bathymetric contour

2.2 The Azores

The islands of the Azores are situated at the triple junction of the American, African and Eurasian plates. The islands of Corvo and Flores, the most westerly, lie to the west of the mid-Atlantic rift and are relatively stable, no significant seismic activity having

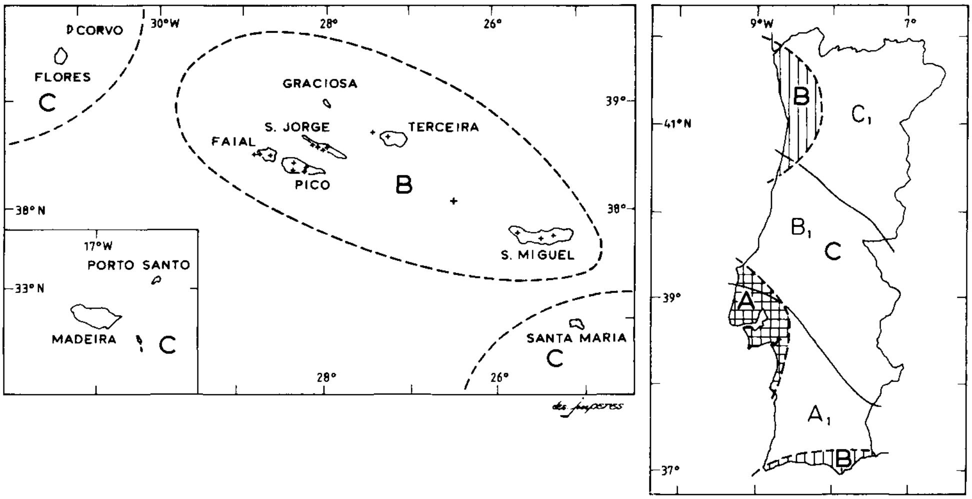

Fig.16.3. Seismic risk zonation in Portugal (very tentative). A1, B1, C1, seismic hazard zonation, based on seismic observation and experimentation (after Oliveira, 1977); A, B, C, seismic risk, taking into account the density of population and the nature of the land use (in the case of the Azores, the crosses represent active volcanoes).

been known to have taken place since the beginning of settlement in the late fifteenth century. The island of Santa Maria, the most southerly in the archipelago, is also relatively stable. There is a quite different situation in the case of islands such as São Miguel, Terceira, Graciosa, São Jorge, Pico and Faial, all of which are characterised by important seismo-volcanic activity. These islands appear to be located in a fan-like zone of expansion between the Gloria fault (an active transform fault) and the mid-Atlantic rift (Fig.16.1). According to Machado (1972-73), the seismic crises in Faial and Pico may be related to rift widening, whereas those in Terceira and São Miguel may be linked to the fan-like expansion just mentioned. The fact is, however, that it has so far proved impossible to establish a convincing tectonic model that can cope with this complicated region. The (still very scanty) information available on the focal mechanism seems to point to active faults of the strike-slip type, some of them dextral, others sinistral. The focal mechanism of earthquakes located on the Azores-Gibraltar fault is usually of the dextral strike-slip type (Moreira, 1982).

In the Azores one has to consider not only the occurrence of isolated earthquakes, such as those in São Miguel (1522), São Jorge (1757), Faial (1926) and Terceira (1980), but also the long series of low-intensity events whose foci seem to be located in the roofs of the magmatic chambers of active volcanoes. In the latest volcanic eruption in the Azores, which occurred on Faial in 1957-58, there was a series of 200 shocks prior to the eruption, and another 400 concomitant with it (Machado, 1970). The most violent seism that shook the Azores may well have been that which struck São Jorge in 1757, reaching an epicentral intensity of XI. The loss of life is estimated to have been 1000, out of a population of 5000, and nearly all houses on the eastern half of the island were ruined (Machado, 1970). This event also caused severe damage in Angra do Heroísmo, the most important town in Terceira.

The 1980 seism in Terceira occurred on New Year's Day; its epicentre was located between Graciosa and Terceira. Graciosa and São Jorge sustained heavy damage to property - there was a spectacular rock fall from the cliffs in São Jorge - but the island most severely affected was Terceira, with a death toll of 60. The earthquake took place in the afternoon; had it occurred during the night, the loss of life would certainly have been far greater. Angra, the town, suffered great destruction, 1800 of its 4600 homes being destroyed, and of the 19 000 houses on the island nearly 10 500 were rendered uninhabitable (Farrica, 1980). The high level of damage, however, was mainly owing to the type of building prevalent on the island, which in most cases fails to comply with the standards set for earthquake resistance. The magnitude of this particular earthquake is estimated to have reached 6.1 to 6.9 on the Richter scale (Moreira, 1982).

The frequency of earthquakes in the Azores has certainly been high, and some have attained considerable magnitude, but if one takes into account the characteristic features of human settlement, one may well conclude that the islands more likely to sustain serious damage lie in a seismic zone of medium risk (Fig.16.3). Santa Maria, Flores and Corvo in the Azores, as well as Madeira and Porto Santo in the Madeira archipelago, are characterised by weak seismic activity and can be regarded as zones of low risk.

3. Volcanic hazards

There is no longer any volcanic activity on the Portuguese mainland. The volcanic complex around Lisbon, nearly 400m thick, was part of a cycle of Mesozoic-Cenozoic igneous activity continuing from 100 million until 60 million years BP (Alves *et al.*, 1986). Volcanism in Porto Santo and Madeira can also be regarded as extinct. Porto Santo is the older island, originating as a submarine volcano between 18 million and 13.5 million years BP and then developing as a subaerial volcano over the next 3 million years. Madeira appears to be composed of five volcanic series, of which the youngest represents volcanic activity that ceased about 300 000 years BP (Ferreira, 1985).

In the Azores, the earliest volcanism is located on Santa Maria, where submarine lavas are covered by Middle and Upper Miocene sediments. On the other islands, radiometric dating indicates essentially Quaternary volcanism (Mitchell-Thomé, 1985). After the beginning of human settlement of the islands by the middle of the fifteenth century, there are records of eruptions of the three main volcanoes in São Miguel (Furnas, Agua de Pau and Sete Cidades), of the most recent stratovolcano in Terceira (Santa Bárbara), of the volcanoes in Pico, São Jorge and Faial, and also of many underwater eruptions (Machado, 1965). Terrestrial eruptions were essentially gentle eruptions of basaltic lavas, but two Plinian eruptions must be mentioned: that of Agua de Pau in 1563, with its abundance of trachytic pumice, and that of Furnas in 1630. Underwater eruptions take on an explosive character as water flows into the vents. The most recent eruption of all was that of Capelinhos, in Faial, in 1957-58. At the outset it was an underwater eruption which took place close to the western end of the island, with explosive activity; later, following the formation of a small island around the vent, its activity became effusive, with a few explosions of Strombolian type. The volume of lava that was ejected is estimated to have been 85 million m^3 (Machado, 1965). There were no casualties but the ash fall damaged houses and farmland on the western end of the island, and 1700 people were rendered homeless (Ribeiro and Brito, 1958).

Overall, the consequences of the historical eruptions cannot be considered catastrophic. During the eruption of the Furnas volcano in 1630, the death toll was 191, but that was probably due to the seisms that occurred during the eruptive process. Likewise, both eruptions on São Jorge (1580 and 1808) seem to have given rise to small *nuées ardentes* that caused the death of 10 people in each event (Machado, 1965). It must be borne in mind, however, that the frequency of eruptions has been relatively high - about 10 in the 500 years since the settlement of the islands - and that, viewed in the context of the geological record, the active volcanoes may still produce much more destructive eruptions in the future. As an illustration, let us recall the Plinian eruptions of the Pico Alto volcano on Terceira, 23 000 and 19 000 years ago, which have been studied by Self (see Fernandes, 1985). The ignimbritic nature of the eruptive materials that covered most of the island (Fig.16.4) showed that those eruptions must have been especially violent. It is easy to imagine the tragic consequences if the island had been inhabited.

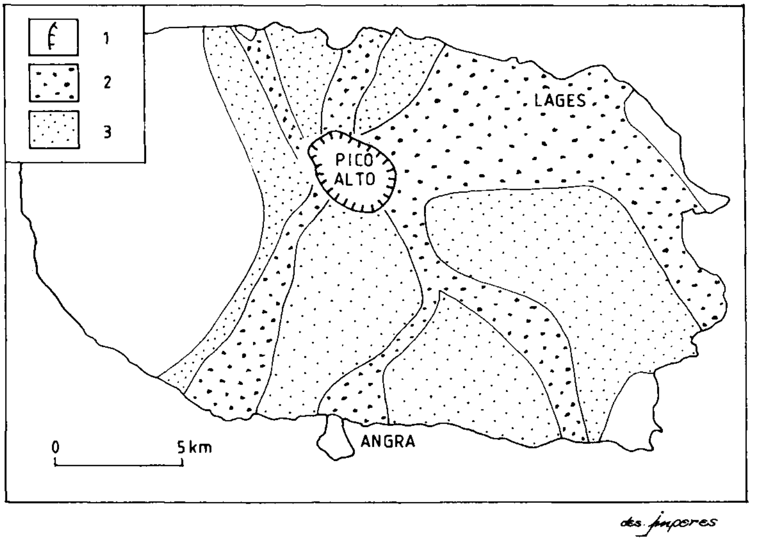

Fig.16.4 Ignimbritic lava flows of the Pico Alto volcano, dated 23 000 and 19 000 BP, after Self (see Fernandes, 1985). 1. Caldera; 2. Ignimbrites; 3. Ignimbrites and pumice

4. Mass movements

4.1. The Portuguese mainland

The mainland of Portugal is fundamentally composed of three morphostructural units: the Hercynian massif, the western and southern Meso-Cenozoic borderlands and the Tertiary Tagus-Sado basin (Fig.16.5B). Of these, the Hercynian massif is by far the largest (70 per cent of the total area) and is also the most stable as regards mass movements. It consists basically of granites and various metasediments with a predominance of slates (Fig.16.5A). Granites appear mainly in the north, where planation surfaces are cut by high and steep valley slopes. It is on such slopes that most of the mass movements in the area of the massif occur. Slope failure is facilitated by the fracture networks in the bedrock and by the heavy and intense rainfall. Metasediments are also fairly common in the north but in the south they become predominant. Multiple discontinuities in these rocks - stratification, schistosity and fracture planes - are favourable to planar landslides, but there are also earthflows affecting mainly the argillaceous soils of less steep areas.

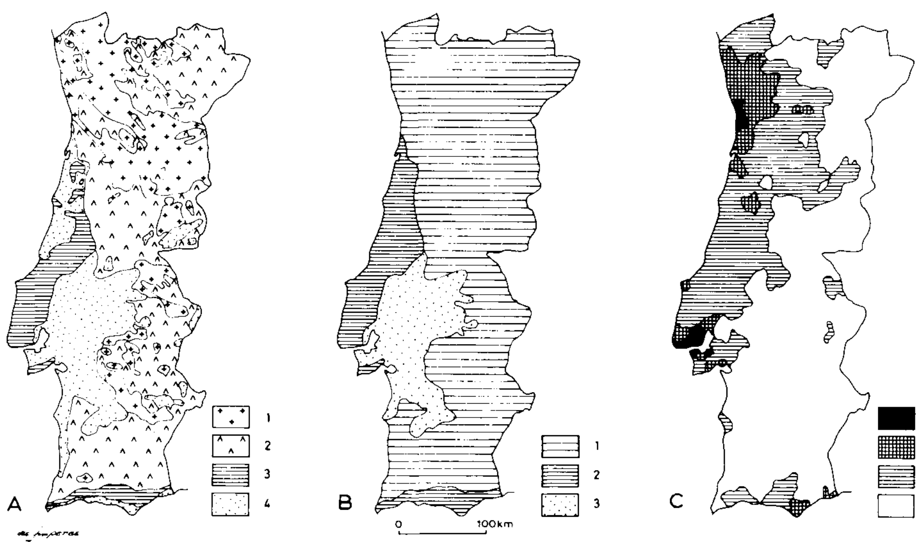

Fig.16.5. Lithology (A), morphostructural units (B) and density of population (C) of the Portuguese mainland (very simplified).
A: 1. Granites; 2. Metasediments; 3. Mesozoic rocks (mainly limestones, marls, sandstones and clays); 4. Cenozoic rocks (mainly sands and sandstones, clays, limestones and marls)
B: 1. Hercynian massif; 2. Meso-Cenozoic borderlands; 3. Tagus-Sado sedimentary basin
C: 1. > 1000 inhabitants per km^2; 2. 200-1000; 3. 50-200; 4. < 50 (after Guichard, 1990)

With the exception of the north-west, where population densities commonly exceed 200 per km^2, the Hercynian massif is thinly populated, with densities generally below 50 per km^2 (Fig.16.5C). At the same time, major engineering works are rare in this area, which can be regarded mainly as a low-risk zone.

The high-risk areas are to be found in the Meso-Cenozoic borderlands and part of the Tagus-Sado basin. Nonetheless, the Lower to Middle Jurassic calcareous zones both in the western and in the southern borderlands (Algarve) can be regarded as relatively stable; only where the limestones press against the Triassic-Hettangian evaporite complex are important landslides likely to happen. This is the situation along the peripheral depression of the Hercynian massif in the Algarve: here, dolomitic limestones form important cliffs that rise above the marly-calcareous complex of Silves. From the Upper Jurassic upwards the lithology becomes more varied, and rocks of different plasticity and porosity alternate frequently. Combined with intensive forms of land use, this is a situation that favours slope instability. The region stretching from Lisbon to Santarém, in which the Meso-Cenozoic borderland and the sedimentary Tagus basin come into contact, can be regarded as paradigmatic: it is in fact here that the most frequent and most important mass movements have occurred, and this is also the region where more thorough research on these phenomena has been carried out (Coelho, 1979; Ferreira, 1984; Ferreira *et al.*, 1987; Rodrigues and Coelho, 1989; Zêzere, 1988).

In the substratum of the region north of Lisbon, resistant rocks (limestones, basalts) alternate with soft rocks (clays and marls). The structural layout is monoclinal and as a rule the strata dip southwards or south-eastwards to the Tagus estuary. Accordingly, the outcrops become younger towards the south and the south-east and the relief consists essentially of cuestas (Arruda dos Vinhos, Lousa-Bucelas, Odivelas-Vialonga). There are two important depressions: the Arruda depression to the north, excavated in the marls and clays of the Abadia complex (Upper Jurassic), and the Loures depression to the south, cut in the clays and marls of the Benfica complex (Palaeogene).

The present-day slope processes comprise chiefly sliding, falling and rill erosion. Limestones and basalts retain rainfall, the groundwater then being slowly absorbed by less permeable formations such as clays and marls. The latter then become plastic and provide sliding surfaces for the overlying limestones or basalts. This alternation of strata of differing permeability and plasticity is the basic cause of slope instability. Landsliding is also very common in superficial deposits, which partly originated under Quaternary cold climatic conditions, and such deposits cover the lower third to one half of most slopes in the region to the north of Lisbon. Rill erosion is mainly linked to clayey sandstones, but it also occurs in marls where they outcrop.

There is no high relief in this area to the north of Lisbon: the higher interfluves rarely exceed 300-350m, but there is great diversity in slope angle. Slope processes overall are most active on slopes steeper than 15°; however, the most important landslides occur on moderate slopes of 5° to 15°. This is related to the more favourable conditions for water storage in such slopes, but at the same time these must reach a minimum angle, normally about 5°, if slope failure is to occur. Another geomorphological characteristic that must be taken into account is the high drainage density of systems converg-

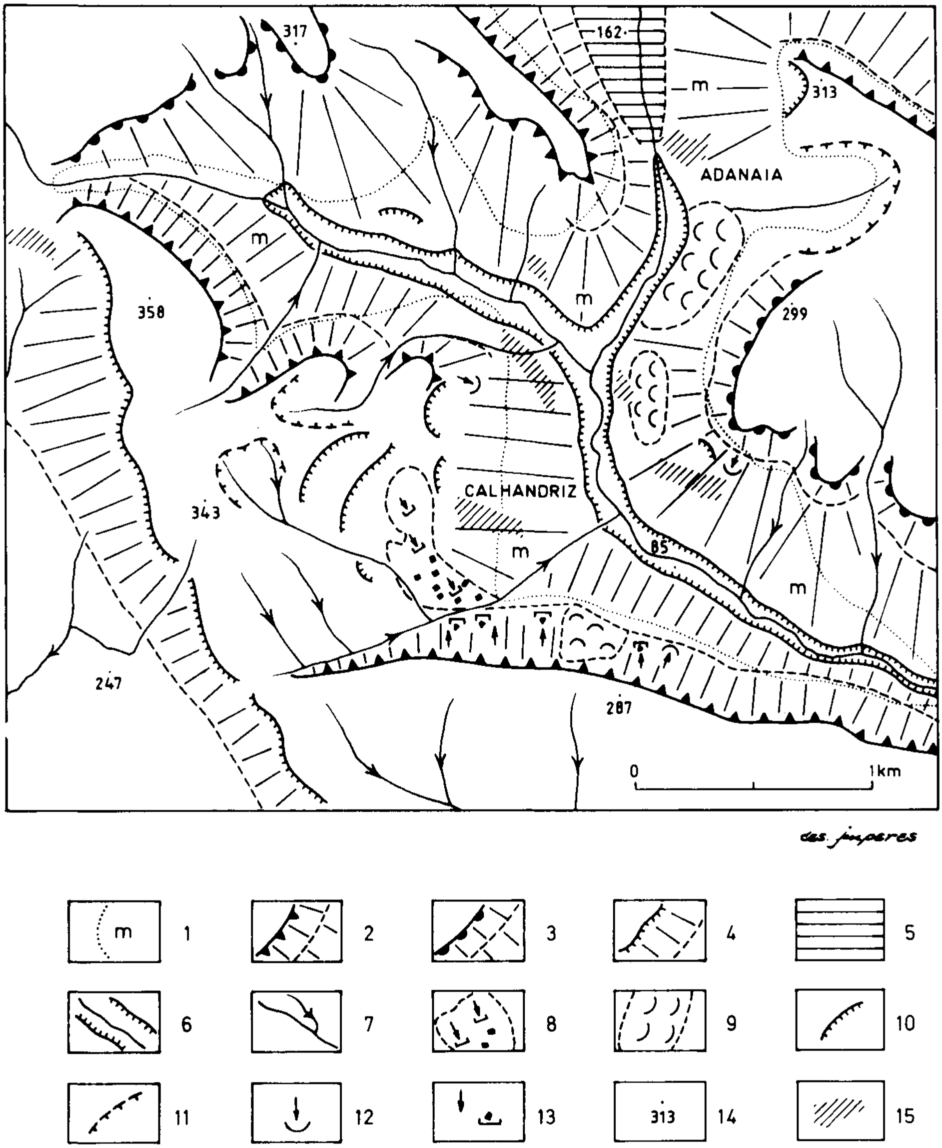

Fig.16.6 Landslides in the Calhandriz area (Ferreira *et al.*, 1987). 1. Abadia Complex (marls and clays with interbedded sandstones); 2. Cuesta scarp; 3. Other cliffs; 4. Probable fault scarp; 5. Ancient valley; 6. Gorge; 7. Streams and gullies; 8. Calhandriz landslide; 9. Other landslides reactivated in February 1979; 10. Landslide scar; 11. Landslide scar, doubtful; 12. Localised landslide; 13. Rockslide; 14. Altitude in metres; 15. Village

ing on the Loures basin, and the existence of only one outlet - the gorge of the river Trancão upstream from Sacavém. This explains the periodic floods in the Loures basin and the drainage problems in the valleys converging on this depression. Similar drainage problems occur in the Arruda dos Vinhos basin.

In addition to the structural and geomorphological conditions just mentioned, certain climatic characteristics also contribute to slope instability. The most significant of these are the irregularity, intensity and concentration of the rainfall. Very heavy rainfall may lead to flash floods in small watercourses, causing rapid bank erosion and many small landslides and earthfalls. Major landslides, however, are related to longer periods of continuous rain. Such was the case at Calhandriz (Fig.16.6) in February 1979, where an event of this type destroyed about ten houses, some of them newly built (Fig.16.7).

Fig.16.7. The Calhandriz landslide that occurred north of Lisbon, in February 1979, destroyed several houses, some of them newly built (photo: A.de Brum Ferreira)

Major landslides have also occurred in the area between Alhandra and Vila Franca de Xira along the right bank of the Tagus, on which the motorway and the conduits conveying the water supply from the rivers Alviela and Tagus to Lisbon have been built. Another classical landslide area is the one around Santarém, along the railway which was built about the middle of the last century (Rodrigues and Coelho, 1989).

It must be pointed out that slope instability is not exclusively, nor even perhaps fundamentally, due to the structural, geomorphological and climatic factors referred to above. Indeed in most cases landsliding is triggered by human activities, especially the destruction of the plant cover, the artificial excavation of potentially unstable slopes and the obstruction of drainage channels in small basins.

4.2. The Azores and Madeira

Surrounded by the sea and composed of volcanic rocks in which layers of lava alternate with layers of pyroclastic material and ash, the islands of the Azores and Madeira possess some cliffed coastlines rising to impressive heights of several hundred metres. They are the sites of frequent rock falls that build up talus slopes at their foot. These screes, locally known as *fajas*, are utilised for agriculture and in the areas of the higher cliffs, the *fajas* are the only populated zones along the coast. Understandably, they constitute areas of high risk for people living there. The latest disaster occurred at Ponta da Faja on the island of Flores (Azores) in December 1987. On that occasion, several houses were buried under 150 000m^3 of debris and the people had to be evacuated (Rodrigues and Coelho, 1989).

Rockfalls are also fairly common on the steep slopes of the valleys; like the coastal cliffs, these may reach several hundred metres in height. On the interfluves, the structure of stratovolcanoes - layers dipping outwards, with permeable lavas alternating with layers of tuff and clay which become plastic under heavy rain - favours debris slides.

In the Azores, the most catastrophic rockfalls are as a rule induced by earthquakes. The earthquake of 1 January 1980, mentioned in section 2.2, produced spectacular rockfalls on São Jorge, and so far the details have not been analysed. The greatest disaster of this kind that occurred in the Azores since the settlement of the islands was, however, the one triggered by the earthquake in Vila Franca do Campo, on São Miguel in 1522. A mudflow formed which buried the town and caused the death of several hundred people. The materials particularly involved were pumice, which was certainly saturated since the mudflow was preceded by heavy rain (Rodrigues and Coelho, 1989).

5. River flooding

5.1. Floods on the main rivers

The Portuguese rivers are characterised by a pluvial regime, and for that reason by a pronounced irregularity in discharge. Winter floods are frequent, while in summer and early autumn discharge falls off to very low levels. The two principal rivers of Portugal, the Douro and the Tagus, are among the three largest watercourses in the Iberian peninsula (the third is the Ebro); the Douro and the Tagus flow from east to west, so that their largest discharges occur in Portugal.

Pardé (1949) described the Douro, in its Portuguese section, as "the most violent river in Europe" on account of its impressive floods. Its largest recorded flood occurred in December 1739 when its discharge is estimated by Pardé (1966) to have reached

19 000m^3s. The mean discharge is 545m^3s. The same author estimates that the flood in December 1961 - January 1962 may have reached 18 000m^3s. For comparison, both of these peak discharges are considerably greater than equivalent events on the Danube (see Chapter 1, Austria). As the river flows through a narrow valley the water level may rise by over 20m for much of its course through Portugal, although the rise diminishes towards its mouth where Porto is situated (Daveau *et al.*, 1978). The most important consequences of the Douro floods are the inundation of the riverside districts of Porto (Ribeira and Miragaia) and of Régua, about 100km farther upstream.

The Tagus floods have different effects, owing to differences in the valley cross-profile. It flows in a gorge as far as Almourol, about 100km upstream from Lisbon, and on reaching the Leziria (floodplain) of the Ribatejo its valley widens. The area liable to inundation is thus much larger in the case of the Tagus valley than in the case of the Douro. The biggest Tagus flood so far recorded appears to have taken place in February 1979, with an estimated return period of 200 years (Sobrinho, 1980); its peak flow then reached 14 160m^3s at Almourol. The flood destroyed many protective dykes, inundated farmland, and cut off many villages, severing roads, railways and industrial areas. Standing on relatively high ground above the floodwaters, Lisbon is not directly affected by the Tagus floods, although it may suffer indirectly from them. In the flood of February 1979, the capital was almost completely deprived of its water supplies for a whole week owing to flooding of the pumping stations which have been built on the floodplain.

Both in Portugal and Spain, dams have been built across the Douro and the Tagus, which obviously affect the behaviour of both rivers. These dams can now prevent most floods, but they can also aggravate the exceptional ones if the reservoirs reach the limits of their capacity and the dams have to be opened during periods of prolonged heavy rain. This was the case in early March 1978: the Tagus flood was essentially the result of the opening of the Spanish dams of Alcântara and Cedillo (Daveau *et al.*, 1978). On the other hand, the building of dams appears to highlight the importance of the spring floods which cause more damage to agriculture than the winter floods (Manzanares and Coutinho, 1982).

On the other large Portuguese rivers, floods are smaller and less hazardous. The river Sado floods an important but thinly populated area, and the river Mondego now and then floods the low-lying areas of Coimbra as well as a broad floodplain farther downstream. Construction of regulation works on the Mondego is in progress.

5.2. Flash floods in small drainage basins

Much more dangerous than the floods on the large rivers are those that can occur in some small drainage basins. This is because of the speed with which they develop and because of the violence of the flow. The flash floods that occurred in the Lisbon area on the night of 25 November and the early hours of 26 November 1967 are sadly remembered for the 400 dead and the severe damage to property which they caused.

While the biggest Douro and Tagus floods are the result of prolonged periods of rain which as a rule occur in mid-winter and are related to active frontal depressions, flash floods are caused by high-intensity rainfalls in short periods (sometimes more than 10mm - even 20mm - in little more than 10-20 minutes), and originate from very convective subtropical depressions which generally occur in the autumn (Ferreira, 1985). Between 19.00h and midnight on 25 November 1967, the rainfall recorded in the Lisbon area reached 129mm at Monte Estoril and 111mm at São Julião do Tojal; these amounts represent about 1.5 times the total monthly average. The intensity per hour reached 30mm at São Julião do Tojal and 60mm at Monte Estoril (Amaral, 1968). As these are areas with many steep slopes, mostly denuded of vegetation and often destabilised by artificial excavations, and with a high drainage density, the effects of the floods can be catastrophic, especially in places where floodplains have been developed for housing. In the Arruda dos Vinhos basin, Quintas, a village built on the floodplain of the Rio Grande da Pipa, was totally destroyed and 90 people lost their lives. Most victims in the Lisbon area lived in very precarious conditions, in shacks or rather rickety houses which could not withstand the destructive effects of the flood (Amaral, 1968).

Rainfall of similar intensity again occurred in the Lisbon area on the night of 18 November and the early hours of 19 November 1983 (Fig.16.8). The meteorological station at Lisbon airport recorded 14mm in 5 minutes, 17mm in 10 minutes, 18.5mm in 15 minutes and 24mm in 30 minutes. Damage to property caused by the ensuing floods was then estimated at 12 000 million Esc (about 140 million US dollars); 1800 families lost their homes and 610 houses were destroyed. Nevertheless, the death toll on that occasion was no more than 10, which can perhaps be explained by better preparedness and a more speedy reaction by both the people and the authorities, prompted by the memory of the 1967 tragedy. In hydrological terms, however, the 1967 episode appears

Fig.16.8. The road along the Trancão valley was washed out during the 1983 flash flood in the Lisbon region (photo: A.de Brum Ferreira).

to have been more serious if one compares the intensity and duration of the rainfall with the times of concentrated discharge in the small watercourses of the area (Costa, 1986).

The precipitation responsible for the 1967 and the 1983 flash floods has a return period well over 100 years and may therefore be regarded as exceptional; on the other hand, only 16 years separate the two events. Unfortunately, with the spread of urban development, other drainage basins whose natural conditions are similar to those in the Lisbon area will become liable to similar hazards. That is precisely what is now happening in the Algarve.

Flash floods are also known in the Azores and Madeira where now and again they cause damage and even casualties. In Madeira, such floods are called *aluviões*. As a rule, they occur in autumn but they can also take place in mid-winter and early spring. They mostly affect the population centres situated near the mouths of torrents and not protected by dykes, such as Machico, Porto da Cruz, Ribeira Brava and Madalena do Mar. Since the eighteenth century, fifteen catastrophic floods have been recorded (Ribeiro, 1985; Quintal and Vieira, 1985). In the Azores, the convective lows that are responsible for the flash floods can occur all the year round, even in summer (Ferreira, 1985). The latest event of this kind occurred on the island of São Miguel on 2 September 1986, causing major damage to property at Povoação and at Faial da Terra (Rebelo and Raposo, 1988).

6. Coast erosion

The coastline of the Portuguese mainland is about 830km long - 600km facing west and 170km facing south, in both directions into the open Atlantic. Coastal erosion is therefore an important consideration, especially in view of the rapid development of coastal areas for tourism in the last 30 years or so and the associated increase in population. In the Algarve, marine erosion is active both along cliffed coasts - as in the case of the Miocene limestones at Praia da Rocha - and in low-lying coastal areas, as in the case of the Ria Formosa (beside Faro), in part owing to ill-devised protection works whose effects make themselves felt only after some years. Mention should also be made of some important construction works built on the west coast that have been seriously damaged from time to time. Examples of this include the harbours of Leixões (Porto) and Sines (on the Alentejo coast). In the case of the latter, the breakwater, which was very expensive in terms of the country's resources, was partly destroyed in the storms of February-March 1978 and February 1979, in conditions not as severe as those that the structure was designed to withstand (Feio, 1980).

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ROMANIA

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1. Introduction

Romania in the south-east of Europe covers an area of 238 391km^2 and presents great natural diversity. Mountains, hills and plains are distributed concentrically in a regular pattern, the land surface rising to a maximum of 2544m in the Carpathian Mountains. The climate is of the humid continental type (Köppen: Daf and Dbf) and the vegetation and soils show differences corresponding particularly to altitude. With some 23 million people, population densities average about 100/km^2 but rise to 150/km^2 or more along certain major valleys, especially in the vicinity of industrial agglomerations. The main factors influencing the range of natural hazards, and their spatial and temporal distribution, are the geological structure, the configuration of the relief, seismic activity, climate and human activity.

The configuration of the relief (Fig.17.1) is a basic controlling factor in the field of natural hazards. The Romanian Carpathians, with moderate to high relief, are fragmented by tectonic depressions and transverse valleys. They consist of discontinuous crystalline massifs, and areas of sedimentary Mesozoic deposits, Palaeogene and Cretaceous flysch and Neogene volcanics. The areas of Romania with hilly relief, rising to 300-800m, are built from sedimentary rocks and comprise (1) the Transylvanian Depression, (2) the Subcarpathians adjoining and paralleling the main Carpathians for a distance of about 550km, comprising Neogene molasse with, locally, Neogene flysch, (3) the Getic Piedmont, and (4) the Moldavian Plateau in the east. The Dobruja Tableland near the Black Sea is a slightly undulating plateau, with some remnants in the north of an old Hercynian chain. The plains of Romania, mantled with loess, alluvium and sand are to be found in the south and west of the country. The relief is variously affected by neotectonic movements, which are most intense in the Carpathians and Subcarpathians where uplift rates are more than 2mm/year; in contrast, parts of the lowlands are subsiding at 1-2mm/year.

The major climatic hazards comprise intense precipitation events, droughts and strong winds. The rainfall regime reflects Romania's position in south-east Europe, affected by the presence and shape of the Carpathian arc but dominated by westerly circulation of air masses. The precipitation shows strong variations, annually, seasonally and monthly; the largest amounts are recorded in years when cyclonic and frontal activity prevails

(Bogdan *et al.*, 1983). Higher quantities fall in the west of the Carpathians, lower amounts in the east. On the southern and south-eastern slopes of the Carpathians, the heavy precipitation is connected with the passage of Mediterranean depressions which import masses of warm moist air from the south. In such conditions, the levels of precipitation that can fall in a short period (c.8-10 days) are two to five times the monthly average, causing large floods (for example, the heavy rain of the period 3-11 October 1982: see Bordei, 1983). The maximum amounts in 24 hours can reach 200-300mm, giving rise to strong erosion of hillslopes. The torrential nature of the precipitation is more pronounced in the east of the country than in the western and central parts. Based on the aggressive character of heavy rainfalls, the country has been divided into ten regions which in turn are classified into three groups: high, medium and low pluvio-denudative potential (Drăgan and Stănescu, 1970).

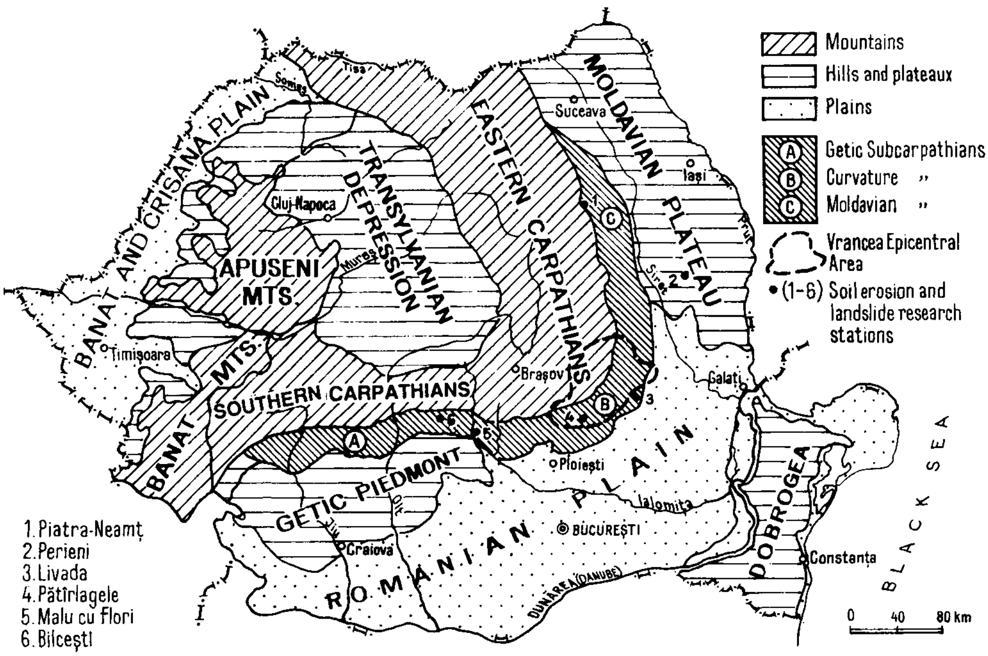


Fig.17.1. Principal relief units in Romania

A whole range of social and human factors influences the occurrence, nature and severity of natural hazards. On the one hand, excessive pressure on the environment through deforestation, improper land use and unsuitable location of industrial activities makes it more prone to natural disasters; on the other hand, afforestation, careful land management, drainage, irrigation and embankments can reduce such risks.

2. Seismicity

Romania is characterised by a high level of seismic activity which, from time to time, shows up in violent earthquakes and related disasters. There are several strongly seismic regions located in Vrancea, Făgăraş, Banat and Maramureş. The Vrancea seismogenic region is said to be the most active sub-crustal earthquake province in the whole of Europe (Mârza and Pantea, 1991): it is the primary focal area responsible for the seismic regime of Romania. It is characterised by the existence of three seismic peaks of activity in every century and by a predominant north-east to south-west direction of preferred propagation of the seismic waves (Constantinescu, 1978; Constantinescu and Enescu, 1985). This explains why the towns and cities located in this seismogenic region and in the south-eastern and central parts of the Romanian Plain, including especially the capital Bucharest, are exposed to such a high seismic risk. This situation is clearly set out in the National Seismic Zoning of Romania.

Two of the most powerful earthquakes to strike Romania occurred on 10 November 1940, magnitude M = 7.4 on the Richter scale, and on 4 March 1977, M = 7.2. Detailed research has been carried out on each. The seismic shocks had marked effects on the relief, particularly evident in the Curvature Subcarpathians (the segment where the Subcarpathians sharply change direction: Fig.17.1) and in the Flysch Carpathians, where large rockfalls, debris flows and landslides were recorded (Rădulescu, 1941; Radu and Spânoche, 1977; Bălteanu, 1979; Mândrescu, 1981). The 1977 earthquake caused the deaths of 1570 people, destroyed no less than 33 000 buildings and caused damage to 765 industrial units (Bălan, Cristescu and Cornea, 1982) (Fig.17.2).

3. Mass movements

Mass movements play a most significant role in the evolution of the relief in the hilly regions and in mountainous areas formed of flysch. The study of these phenomena in Romania has a long tradition, and both geomorphological and engineering geological investigations provide the bases for their classification according to a range of criteria (Mihăilescu, 1939; Tufescu, 1966) and for large-scale and medium-scale mapping. Geomorphological maps on scales from 1:10 000 to 1:200 000, including maps of present-day geomorphological processes, morphodynamic maps and hazard maps have been compiled. Syntheses across the whole country lay stress upon the spatial differentiation of landslide potential (Tufescu, 1966) and the spatial distribution of landslides grouped by frequency of occurrence (Posea *et al.*, 1974), and outline the areas of highest incidence (Bălteanu and Mateescu, 1975). The distribution and diversity of mass movements is controlled by slope angle, by lithology, by the level of neotectonic activity and by the different patterns of land use and land management.

Several studies emphasise the role of intense rainfall events. For example, in both 1969 and 1975, across different counties (Vaslui, Iaşi, Mehedinţi, Gorj and Vâlcea), 11 000ha were rendered unusable for agriculture. Mapping of active landslides in ten

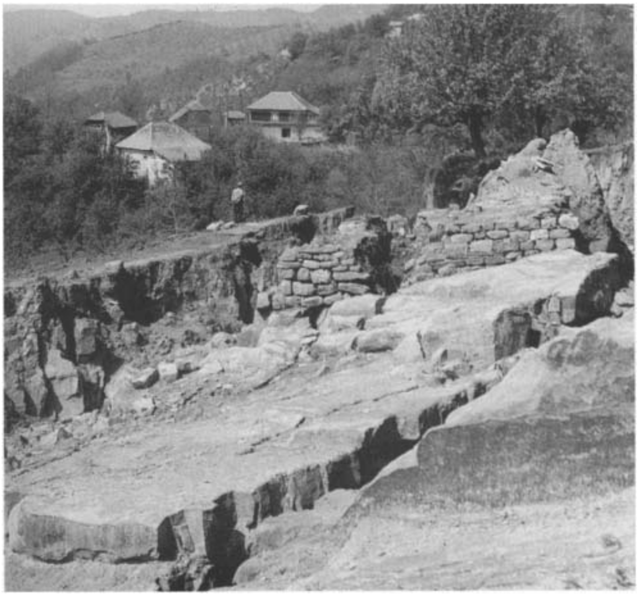


Fig.17.2. Deep-seated landslide triggered by the earthquake of 4 March 1977 in the village of Colţi, Curvature Subcarpathians (Photo: D.Bălteanu)

counties consisting mainly of hilly terrain shows that, between 1969 and 1975, 14 600 ha had become unusable for agriculture, the productive potential of a further 22 000ha was partially affected, 22 000ha required urgent reafforestation, and land-use changes had to be made on yet another 22 000ha (Bally and Stănescu, 1977). In 1970 alone, a year with particularly heavy rainfall, 20 000ha were affected by landslides, and large areas of farmland, buildings and lines of communication were destroyed. Quantitative estimates of slope denudation (Motoç, 1982) indicate that landsliding is most pronounced in the Subcarpathians of Vrancea and Vâlcea (4.7-4.8t/ha/year), the Transylvanian Plain (4.5t/ha/year), the central part of the Moldavian Plateau (4.4t/ha/year), and the Sub-Carpathians of Buzău and Gorj, together with the south-western part of the Târnave Plateau (3.8t/ha/year). There are important regional differences among the types of landslide, the delivery coefficients of materials from the slopes into the channels, and the risks for different human activities.

In the Subcarpathians, formed predominantly of folded and faulted Neogene molasse, the slopes are highly unstable (Figs.17.3 and 17.4). The distribution and variety of mass movements are strongly related to the lithology and to land use and land management. The most frequent types are translational slides, medium- to deep-seated rotational slides and mudflows. Shallow translational slides affecting the top 1-1.5m of the slope materials have the widest distribution and are especially active during spring snow-melt and heavy summer rainfall. Some remain active for 2-3 years, while others are covered with vegetation after a few months. Deep-seated slides are triggered by many different causes - heavy rainfall, strong earthquakes (Fig.17.2), and overloading of the slopes either naturally or due to human activity, are the commonest. Mudflows are frequent after heavy rain on deforested slopes (Fig.17.5) and can exceed 1km or more in length. Rockfalls and debris flows are most often triggered by earthquakes: during the earthquake of 4 March 1977, debris flows with volumes up to 360m^3 occurred on the south- and east-facing slopes. Slope instability varies according to drainage basin and to patterns of neotectonic activity. The worst affected area is that of the Curvature Subcarpathians, included in the seismogenic region of Vrancea, where rates of denudation

Fig.17.3. Complex mass movements on the southern slope of Blidisel Hill (Buzău Subcarpathians), built of Neogene molasse (Photo: D.Bălteanu)

attributable to mass movements, calculated on the basis of data obtained over a 12-year period on catchments from 0.33 to 4.3km^2 in area, are from 0.5 to 10mm/year. The highest rates correspond to years with high rainfall, and the recurrence intervals of movement are 5-7 years (Bălteanu, 1986).

In the Eastern Carpathians, made up of Cretaceous and Palaeogene flysch, the colluvial deposits, considered periglacial or immediately post-glacial and 10-30m thick, are periodically affected or re-activated by the increasing tendency towards valley deepening, and by anthropogenic deforestation. The greatest risks are attached to the re-activation of deep-seated landslides which often seriously affect both towns and lines of communication, sometimes even blocking valleys partially or wholly.

Fig.17.4. Slope affected by deep-seated landslides in the Buzău Subcarpathians (Photo: D.Bălteanu)

Fig.17.5. Earthflow in the upper basin of the Bălăneasa river, Buzău Subcarpathians (Photo: D.Bălteanu)

In the Moldavian Plateau, the areas most affected by landslides are the steep slopes built out of alternations of marls, clays, conglomerates and calcareous sandstones. In the Transylvanian Plain (part of the Transylvanian Plateau), the slopes affected by landsliding consist of Sarmatian clays and marls, mantled by thick Pleistocene and Holocene colluvial deposits (Morariu *et al.*, 1964). Deep-seated landslides triggered by heavy rainfall are known locally as "glimee".

Another area with a high sliding potential lies in the central and eastern part of the Târnave Plateau, where slopes are developed on marls and clays with intercalations of sandstones and sands.

Landslides are a major hazard also in the case of deep quarry slopes, waste dumps and decantation lakes. When the reservoir of Certej-Săcărâmb, near the town of Deva, failed on 31 October 1971, 50 people died and there was considerable damage to property.

In the Carpathian Mountains, rockfalls, debris flows and toppling failures frequently occur on the steeper slopes developed on crystalline rocks, sandstones and conglomerates, and are a major risk to forest roads and villages. In the alpine zone, avalanches are frequent on the steep sides of glacial cirques and valleys, causing temporary blockage of winter traffic on the trans-Carpathian roads and damaging winter-sports amenities.

4. Soil erosion

Sheet erosion and gully erosion affect in various degrees about two-thirds of Romania, principally the hilly and mountainous regions. As early as the second half of the nineteenth century, scientific attention had been drawn to the great extent of the area affected and the detrimental influence on agriculture. The first inventory of eroded soils, made in 1953, revealed a total area of 82 920km^2 affected. Using field mapping at various scales and the monitoring of experimental plots, it was possible to quantify the erosion risk on different angles of slope and different land uses (Motoç, 1982). Agricultural land with slopes steeper than 5 per cent represents 42.6 per cent of the eroded areas; dependent on the intensity of the rainfall, the resistance of the soil and the exact type of land use, this category has a high erosion potential. 20.6 per cent of the agricultural land is affected by intense to very intense erosion with a potential rate of soil removal in the range 8-16t/ha/year; 19 per cent is subject to medium to intense erosion (2-8t/ha/year); and 3 per cent is subject to slight erosion risk (< 2t/ha/year). The highest erosion risks occur in the Curvature Subcarpathians, the north of the Getic Plateau, the central part of the Moldavian Plateau and the west of the Transylvanian Plateau.

Large areas are also affected by gully erosion, which every year renders another 5000ha unfit for cultivation, representing an annual soil loss of 30 million t. The worst affected areas are in the Curvature Subcarpathians where potential soil losses range from 12.5 to 24.4t/ha/year; in the Getic Subcarpathians, corresponding values are 8-8.5t/ha/year. The rapid extension of gullying in the Subcarpathians is connected with the poorly consolidated rocks, the rainfall intensity, the tectonic mobility and improper forms of land use.

The steep slopes of the Moldavian Plateau, comprising the cuestas of the Tutova and Covurlui Hills, run a higher risk of gully erosion than the Transylvanian Depression, where the rainfall is less torrential and the people have traditionally taken measures to combat erosion.

5. Floods

The flood hazard has one of the most serious impacts on settlements, communications and agriculture in Romania. The country has *c*.4000 river basins with areas greater than 10km^2; a total of about 35 000km^2, mostly along the Danube, the main rivers of the Romanian Plain (the Siret, Buzău, Ialomiţa, Argeş and Jiu) and of the Banat-Crişana Plain (the Someş, the three Criş rivers and the Mureş), is potentially at risk from flooding. In the mountainous and hilly areas, where the channels are steep (often 10-20 per cent) and the floodplains are narrow, except in some basins, high discharges cause strong bank erosion and landslides which can obstruct valleys; the greatest risk is in the flatter and lower-lying areas.

Floods are generated by prolonged heavy rainfall, snowmelt, or both. The frequency of their occurrence is greatest in spring (30-50 per cent) and summer, and the role of antecedent rainfall in causing rapid runoff on already saturated areas is important. The spatial incidence of serious flooding is largely determined by human activity. Deforestation undertaken in many parts of the Carpathians enhances not only runoff but also soil erosion, the products of which are transported and deposited in lowland channels whose beds are thus raised, increasing the risk of bank overflow. During major floods, the dams and embankments built along the Danube and along the main watercourses have sometimes proved inadequate to control the flows and in some emergencies have even proved detrimental.

The most recent catastrophic floods were recorded in 1969 (Fig.17.6), 1970, 1975 and 1991. Less disastrous events took place in 1932, 1938 and 1948, affecting smaller areas.

Fig.17.6. Destruction of the Buzău-Nehoiaş railway in June 1969 by flooding on the Buzău river at Păltineni (Photo: D.Bălteanu)

5.1. Regional patterns of flooding

5.1.1 The central-western part of Romania comprises the Transylvanian Depression, the western slopes of the Eastern Carpathians, the Apuseni mountains, the hills and plains of Banat and Crişana. Here, flooding is related to heavy rainfall brought either by westerly airstreams and associated depressions of North Atlantic origin, or by more southerly moist airmasses that have followed a Mediterranean route. Most commonly, flooding occurs after prolonged and repeated intervals of soil-saturating rainfall, producing a succession of flood waves on the rivers. The floods that occurred on 12-14 May 1970 were fed by abundant rainfall over some 15 000km^2 and, together with rapid snow-melt in the mountains, caused damage to 1500 towns and villages, numerous factories, roads and railways, and in total affected 10 584km^2 (Podani and Zăvoianu, 1971).

5.1.2. Southern Romania Consisting of the area extending from the Southern Carpathians and the Getic Piedmont to the Romanian Plain, this region is liable to receive abundant torrential rainfall at times from Mediterranean depressions. The generation of rapid, successive flood waves on the rivers flowing to the Danube produces catastrophic flooding, especially in confluence areas and the low subsiding sector of the plain. On 1-4 July 1975, disastrous floods were recorded on the Jiu, Argeş, Ialomiţa, Prahova, Teleajen and Buzau rivers, causing damage to 270 industrial enterprises, numerous towns and villages and devastating 8000km^2 of agricultural land (Zăvoianu and Podani, 1977).

5.1.3. Eastern Romania experiences floods generated by heavy rainfall associated with a blocking circulation in the Eastern Carpathians and with retrogressive movement of Black Sea depressions. They affect the rivers draining the Eastern Carpathians and Sub-carpathians and the Moldavian Plateau. A particular case was the episode of 26-30 July 1991, when there was flooding on the rivers Moldova, Bistriţa, Trotuş, Tazlău, Putna and Buzău. There were 110 deaths, 1100 houses were destroyed and 800km^2 of arable land damaged. The worst affected area was the Tazlău valley because the 4-million-m^3 reservoir dam at Belci, built in 1962, collapsed.

5.1.4. Local floods connected with heavy convectional rain are frequent in summer, but are restricted to small catchments.

6. Regional differentiation of geomorphological hazards

The spatial distribution of geomorphological hazards (Fig. 17.7) is linked on the one hand with the differentiation of natural environmental conditions - relief, structure and tectonics, climate - and on the other hand with the uneven distribution of population and economic activity.

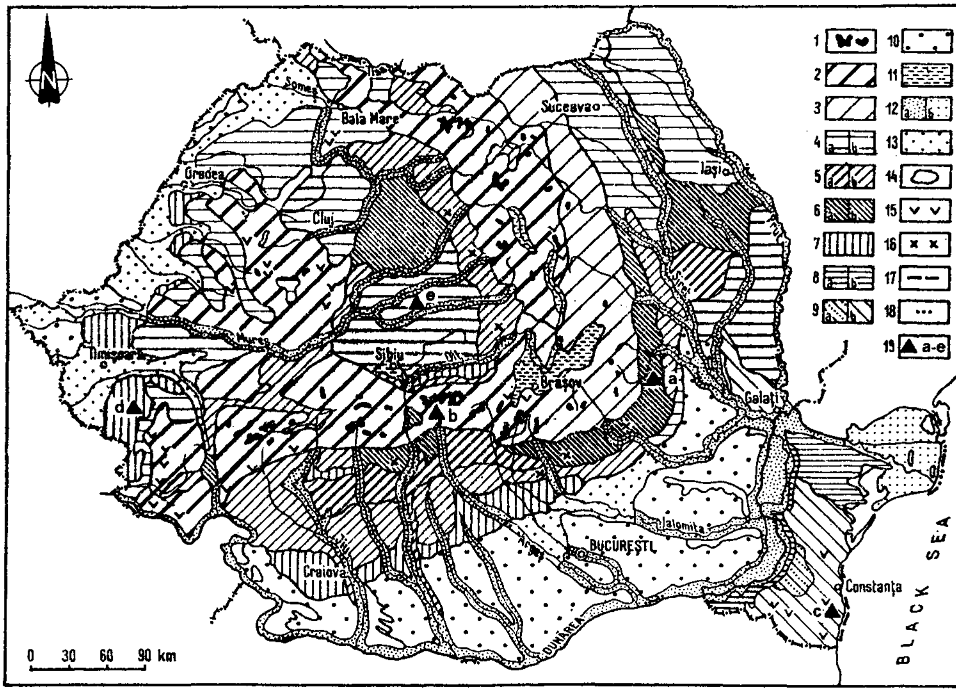


Fig.17.7. Geomorphological hazards in Romania.
Mountain areas: 1. Avalanches, rill erosion; 2. Torrents, rockfalls, topples; 3. Torrents, landslides, mudflows;
Hilly and tableland areas: 4. Sheet and gully erosion with mass movements: a) intense, b) moderate; 5. Gully and sheet erosion with mass movements: a) intense, b) moderate; 6. Mass movements with sheet and gully erosion: a) intense, b) moderate; 7. Weak to moderate sheet erosion on valley slopes;
Plains and low tablelands: 8. Sheet and gully erosion with piping: a) intense, b) moderate; 9. Sheet erosion and piping: a) intense, b) moderate; 10. Piping in loess; 11. Colluvial and alluvial deposition; 12. a) Alluvial deposition; b) alluvial and biogenic processes in delta region; 13. Alluvial deposits of major floods; 14. Deflation and aeolian deposition; 15. Karst solution processes; 16. Salt solution; 17. Abrasion; 18. Shoreline deposition; 19. Seismogenic regions: a) Vrancea, b) Făgăraş, c) Pontic, d) Danubian and Banatic, e) Târnave

In the mountainous areas of the high Carpathians above about 1700m, avalanches, rockfalls and debris flows offer the main geomorphological risks to the relatively scattered population and the centres of tourism and recreation. In the Flysch (Eastern) Carpathians, landslides and mudflows are more significant risks, affecting settlements, roads and railways. High discharges on the rivers lead to bank erosion and undercutting of slopes, causing landslides and some flooding of broader basins.

The hilly areas and plateaus support denser populations and are more intensively used for agriculture and forestry. Severe soil erosion, including gullying, together with landslides and mudflows affect some 30-40 per cent of the cultivated land. Flooding becomes an important risk to valley settlements, lines of communication and fields next to the main rivers.

In the plains, flooding and seismic hazards are the main threat. Towns and villages, factories and farms located on floodplains, and more especially those in subsiding areas, are liable to catastrophic inundation. The seismic risk is most acute in the eastern and central parts of the Romanian plain and in the Banat plain.

7. Two case studies from the Buzău Carpathians*

The Buzău Carpathians and the Subcarpathians have suffered from the greatest mobility of the relief throughout the Pleistocene and Holocene. There is an extensive literature available about the processes and range of landforms, which are also depicted on medium-scale and some large-scale surveys. Some experimental sites have been established and monitored. Two examples will be given.

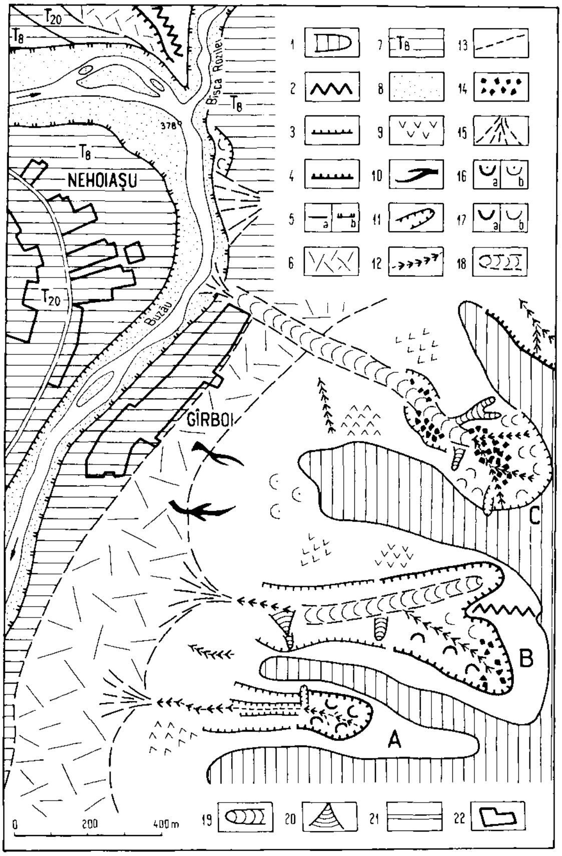
7.1. The Nehoiaşu test area

This lies at the western extremity of Ivăneţu summit, on the slope facing the Buzău valley (Fig. 17.8). Geologically, it is underlain by strongly tectonised Palaeogene flysch trending in a north-east to south-west direction. The Kliwa gritstone, including poorly cemented psammites and aleurites, facilitates the undermining of gritstone blocks. The Fusaru grit flysch (Oligocene) is widespread, and its role in triggering many slope processes is connected with the matrix-to-arenite ratio (1:2) and the predominance of calcareous cement. The markedly schistose character of menilites and disodiles is another factor that contributes to bedrock dislocation and block sliding.

Although the Ivăneţu summit has a forested western slope, the latter has nevertheless suffered from a series of landslides, rock and earth falls and mudflows during the last century, re-activated in more recent times by heavy rainfall (for example, 1939, 1952, 1957, 1991: Mihăilescu, 1940) or by major earthquakes (such as 1940, 1977, 1986). Three slides have been the subject of detailed investigations, as shown on Fig. 17.8.

7.1.1. Slide A is located 800m south-east of Gârboi; its 400m-long track is underlain by older material that was active in 1939 and 1952. A torrent developed along the slide

* Based on fieldwork and mapping by A.Cioacă, M.Dinu and M.Constantin



1. Smooth flat summits
2. Ridges
3. Scarps up to 30m high
4. Scarps over 30m high
5. Actively undercut river-banks
   a) less than 2m high
   b) more than 2m high
6. Glacis
7. River terraces
   (T_8,T_{20} - relative height in m)
8. Floodplain
9. Sheetwash
10. Gully erosion
11. Gully head
12. Torrent valleys
13. Small valleys
14. Rockfall
15. Alluvial fan
16. Deep-seated slides
   a) active, b) relict
17. Surficial slides
   a) active, b) relict
18. Landslide track
19. Mudflow
20. Mudflow cone
21. Roads
22. Settlements

Fig.17.8. Geomorphological sketch of the Nehoiaşu test area

track forms a narrow trench 8-10m wide, providing a cross-section which reveals something of the sequence and chronology of the displaced material. The landslide scar shows several lateral active scarps up to 30m high with flat tops covered here and there with forest. Below them are active sliding layers moving over older material (Marinescu, 1956). The basal shear surface is formed in greyish Eocene clays and marls with thin gritstone intercalations; these are overlain by Oligocene menilites seen in the scars.

7.1.2. Slide B located in the source area of the Stănicu torrent is considerably larger. The double scar divided by a short ridge is 30-40m high and extends about 400m. The bowl to the south of this ridge is the more active of the two, as the profusion of fallen Oligocene gritstone blocks in front of it proves. The fallen rock forms a kind of talus lying over the folded material of previous slides. The northern bowl is less deep and largely covered by forest. The track of the slide leading from this double head is about 600m long and is mostly supplied by the southern bowl. Trees on the sliding debris are deformed in their growth around the fallen blocks but are otherwise quite straight; they are generally not more than 15-16 years old (in April 1992) which agrees with local reports that the rockfalls began after the 1977 earthquake.

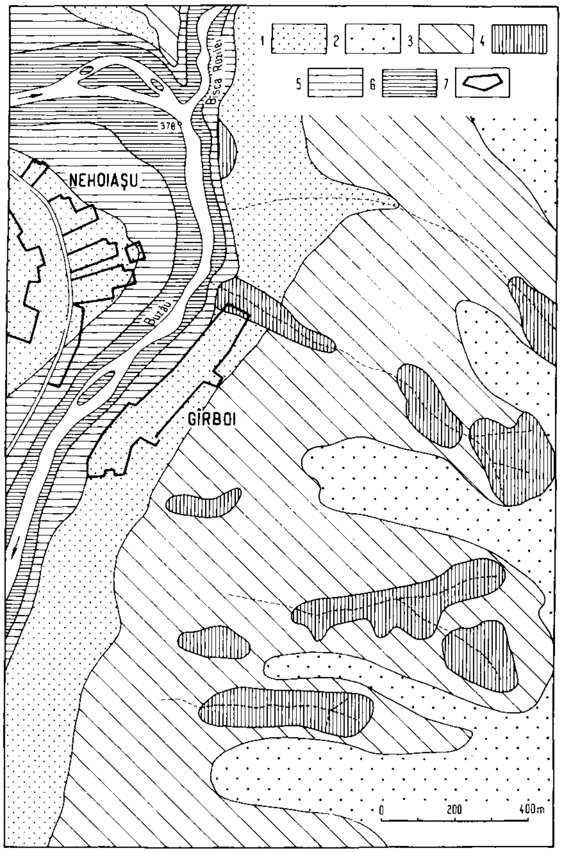
7.1.3. Slide C farther north is an older feature but was re-activated in 1939. It developed in the source area of a torrent (Mihăilescu, 1940; Marinescu, 1956), with a scar now up to 40m high. The bowl at its head consists of a mass of old inactive slide material, engulfing Oligocene gritstone or menilite. Farther down, fallen blocks flank the moving material which supplies a long track reaching the Buzău river in a small fan. Slide C has developed through headward retreat of the scar, up to the point where it affected the menilites which are more resistant than the marl, clay and fine gritstone complex beneath. The development of an overhanging ledge of menilite facilitated the collapse of some large blocks (up to $3m^3$) during earthquakes.

Fig.17.9 shows the degree of risk in the area, taking into account the periodic re-activation of slope processes and the simultaneous recession of the scars (Bălteanu *et al.*, 1989).

7.2. The Păltiniş-Aneniş test area

Extending on either side of the Bâsca Rozilei valley (Fig.17.10), the area lies in the contact zones of the Fusaru gritstone flysch, the Bisericani schistose flysch and the Kliwa gritstone. These are overlain by highly shattered menilite schists subject to major slides and rockfalls.

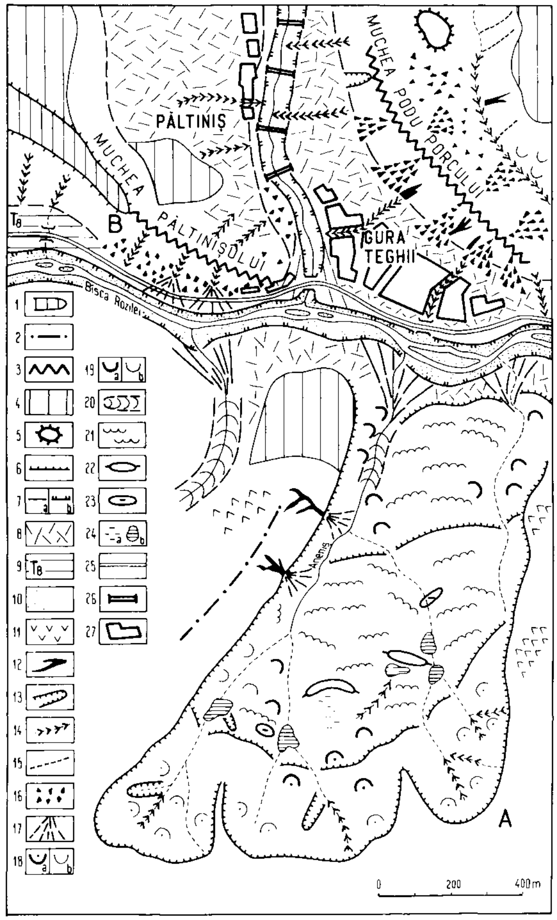
7.2.1. The Aneniş landslide is located on the southern slope of the Bâsca Rozilei valley and is relatively large - 1.5km in length and 1km wide in the source area. It started a century ago when there was extensive felling of trees for forestry purposes. After having reached a temporary balance, sliding began again, re-activated by the 1940 and 1977 earthquakes (Calotă *et al.*, 1988). Investigations that were conducted 15 years later (May 1992) were hardly able to recognise the scar of the 4 March 1977 shock, because solifluction and sheet wash had smoothed it out. Today, there are several springs related to broken marl lenses in the old sliding mass, supplying small lakes or patches of wet ground that have formed between or among the landslide lobes. The old scar lies at an altitude of 770-790m and is less than 20m high; sloping at 20°-25°, it is almost concordant with the local dip of the gritstone layers (Ielenicz, 1970, 1972). Although no longer active, some deep active slides have recently developed at its base. The fissure produced by the 1977 earthquake has been covered with soliflucted debris and new slide material. Torrents have developed along the margins of the landslide, of which the Aneniş is over 1.5km long.



1. Glacis and river terraces with low risk of landslides but some risk of sheetwash and underground piping; 2. Summits with low risk of sheet slides, possible re-activation of scars and gully source areas; 3. Slopes with moderate risk of landsliding, mudflow and extension of gully erosion; 4. Slopes with high risk of sheet slides, mudflows and major rockfalls; 5. Major river channel with moderate risk from overbank flow during severe floods; 6. Major river channel with high risk of flooding and bank erosion; 7. Settlements

Fig.17.9. Hazard zone map of the Nehoiaşu test area.

7.2.2. The Păltiniş summit together with the Podu Porcului summit stands to the north of, and towers over, the Bâsca Rozilei valley. More than 400m long with steep forested slopes, it is built of layers of siliceous gritstone with calcareous cement, up to 3m thick, separated by clay and marl horizons. The gritstone easily breaks to produce detached blocks (2 x 1.5 x 3m) that stand in a precarious equilibrium. Temporarily, the forest



1. Smooth flat summits
2. Broad undulating summits with hills and cols
3. Ridges
4. Fragments of quasi-horizontal surfaces
5. Outlier
6. Scarps up to 50m high
7. Actively undercut river-banks
   a) less than 2m high
   b) over 2m high
8. Glacis
9. River terraces (T_8 - relative height in m)
10. Floodplain
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16. Rockfall
17. Alluvial cone
18. Deep-seated slides
    a) active, b) relict
19. Surficial slides
    a) active, b) relict
20. Landslide track
21. Solifluction area
22. Bulge on surface of landslide
23. Micro-depressions within the landslide
24. Moist areas (a) and ponds (b) on the landslide surface
25. Roads
26. Dams
27. Settlements

Fig.17.10. Geomorphological sketch of the Păltiniş-Aneniş test area.

provides a degree of stability, but during spells of heavy rain (e.g. 26-30 June 1991) and especially during seismic disturbances, large blocks can tumble down into the valley, as was witnessed during the last earthquake. Houses were destroyed by their impact whose high energy is derived from the slope steepness (over 40 degrees and a length of 200m). The local inhabitants have devised some simple methods of protection: they use steel cables to anchor certain blocks symmetrically from two slope edges, or attach the cables to the oldest best-rooted trees. So far the method has worked well for the large blocks, but of course it is impossible to anchor every block that may present a threat.

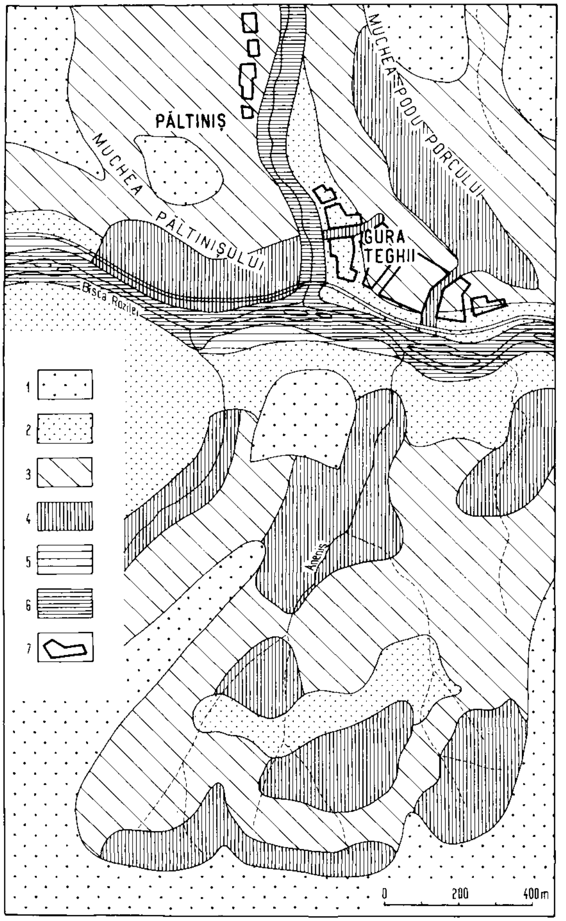

Fig.17.11. Hazard zone map of the Păltiniş-Aneniş test area.

1. Summits with low risk of sheet slides, possible re-activation of scars and gully source areas; 2. Slopes with low risk of landslides but some risk of sheetwash and underground piping; 3. Slopes with moderate risk of landsliding, extension of gully erosion and accumulation of blocks; 4. Slopes with high risk of deep-seated slides and sheet slides, re-activation of landslide tracks, large rockfalls and formation of talus cones; 5. Major river channel with moderate risk of overbank flow during severe floods; 6. Major channel with high risk of flooding and bank erosion; 7. Settlements

In 1991 after the rainy period in late June, saturation of the slope materials triggered sliding and falls of large blocks (up to $2m^3$) into the flooded Păltiniş river. The blocks demolished the fragile structures used to dam the water and pushed the channel to the east. The force of the floodwater coupled with the new curvature of the channel devastated every household and field with crops on its path.

Fig.17.11 shows a hazard zone map of this area, suggesting a major incidence of dangerous landslides and rockfalls affecting the villages of Păltiniş and Gura Teghii.

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SPAIN

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1. Introduction

With its great variety of climatic, geological and morphodynamic environments, Spain is subject to practically every kind of natural hazard (Fig.18.1). The temporal and spatial distribution of these hazards is, however, very irregular. Some processes, such as tsunamis, have occurred roughly once in a millenium, whereas others, such as floods, take place almost every year in some part of the country. Certain hazards, such as volcanism, affect only a small part of the kingdom (the Canary Islands); others, in contrast, are very widespread as in the case of floods and mass movements.

The losses resulting from these hazardous processes have been estimated by Ayala *et al.* (1987), for the 30-year period from 1986 to 2016, to be between 49 and 81 billion (10^9) U.S. dollars (Table 18.1). The loss of life could be between 1000 and 40 000 for the

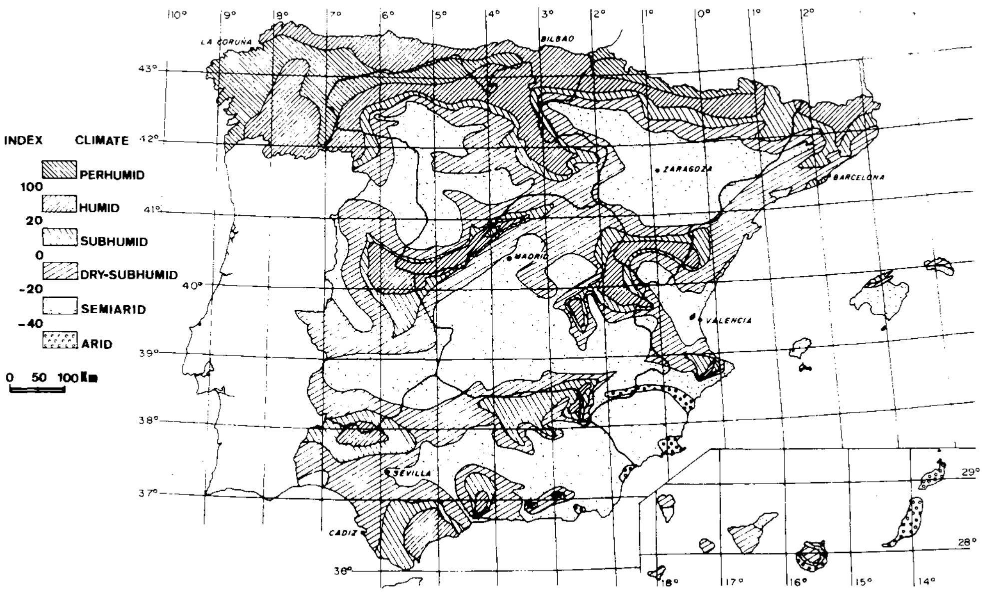

Fig.18.1. Simplified climatic map of Spain, based on Thornthwaite's humidity index (after Justo and Cuéllar, 1972)

same period, depending on the hypothesis adopted. It has also been estimated that a reduction of 69 per cent in these losses could be achieved by introducing mitigating measures at a cost equivalent to 11 per cent of the expected damage.

This article presents a brief review of the situation concerning the various geomorphological hazards in the country, including some information about existing programmes for research, control and mitigation.

2. Seismic hazards

The distribution of seismic activity is shown in Figure 18.2. The main seismic area in the south-south-east is related to the collision zone between the African plate and the Iberian sub-plate. The suture zone between the latter and the European plate, in the Pyrenees, is the other zone with significant historical seismicity. Some seismic activity related to volcanic phenomena also occurs in the Canary Islands. The main sources of seismic data in Spain are the Banco de datos sismológicos of the National Geographical Institute, Madrid, and the Catálogo general de isosistas (Mezcua, 1982).

Studies of seismic hazards in Spain have followed two main approaches: first, a deterministic approach based on the identification of seismotectonic provinces characterised by their historical seismicity, or on the assignment of hazard levels corresponding to the greatest known events in the historical record, for each location; and secondly, a probabilistic approach which tries to establish, statistically from past records, the probability of future events of specific magnitudes or intensities.

Examples of the first type of approach are the work of the IGC-IGME (Instituto Geográfico y Catastral and Instituto Geológico y Minero de España) (1966) and Martín (1984). The second kind of approach is exemplified in the work of Munuera (1969) and

Table 18.1. Estimated losses (in millions of U.S. dollars) and mitigation costs of geological and geomorphological hazards in Spain, for the 30-year period 1986-2016, according to the maximum (a) and most probable (b) hypotheses (Ayala *et al.*, 1987)

Hazard	Number of deaths	Economic losses	Estimated cost of mitigation measures	Estimated reduction of losses if mitigation measures are implemented
Floods				
(a)	-	28 234	11 689	14 823
(b)	500-1000	28 234	11 689	14 823
Earthquakes				
(a)	6000-30 000	26 843	26 843	13 421
(b)	0-20	847	84	423
Mass movements				
(a)	0-500	8959	922	8063
(b)	0-70	7657	788	6891
Soil erosion				
(a)	-	8707	3979	5747
(b)	0	8707	3979	5747
Tsunamis				
(a)	1000-10 000	3919	2469	3723
(b)	0	0	0	0
Coastal erosion				
(a)	-	3120	1426	2059
(b)	0	3120	1426	2059
Swelling clays				
(a)	-	1042	52	1032
(b)	0	1042	52	1032
Volcanism				
(a)	100-1000	162	5	26
(b)	0-10	20	0.7	3

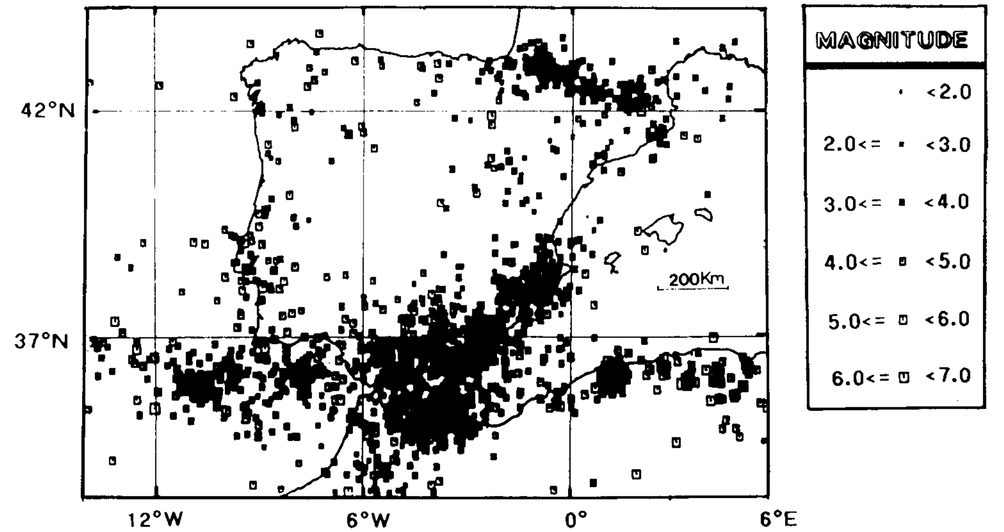

Fig.18.2. Seismicity of the Iberian Peninsula and adjacent areas (data from the Seismic Data Bank of the National Geographical Institute, Madrid)

Roca and Udías (1976). The method proposed by Cornell and later developed by McGuire (McGuire, 1976) has also been extensively used, for instance in Andalusia (Muñoz, 1983) or for the whole of Spain (Martín, 1984). Other interesting regional studies include those by Ibargüen (1985) in Murcia, and Gentil (1989) in Sevilla. The recently completed map of seismic hazards with a return period of 1000 years is shown in Figure 18.3.

Studies on the economic significance of seismic hazards have been carried out for the whole country (Ayala *et al.*, 1987) and, with greater detail, for Andalusia (Martín, 1991).

Among the studies currently in progress, it is worth mentioning a thorough revision and improvement of the catalogue of historical seismicity by the Instituto Geográfico Nacional (National Geographical Institute), ENRESA (Empresa Nacional de Residuos, S.A.) and the Consejo de Seguridad Nuclear (Council for Nuclear Safety), and the new seismo-tectonic zoning made by the National Geographical Institute and the Instituto Tecnológico Geominero de España (Technological Geomining Institute of Spain).

3. Volcanic hazards

The only area with active volcanism is the Canary Islands. This is an unusual case of a passive continental margin which has experienced magmatic activity since at least the upper Cretaceous. There have been eruptions on four islands, La Palma, Hierro,

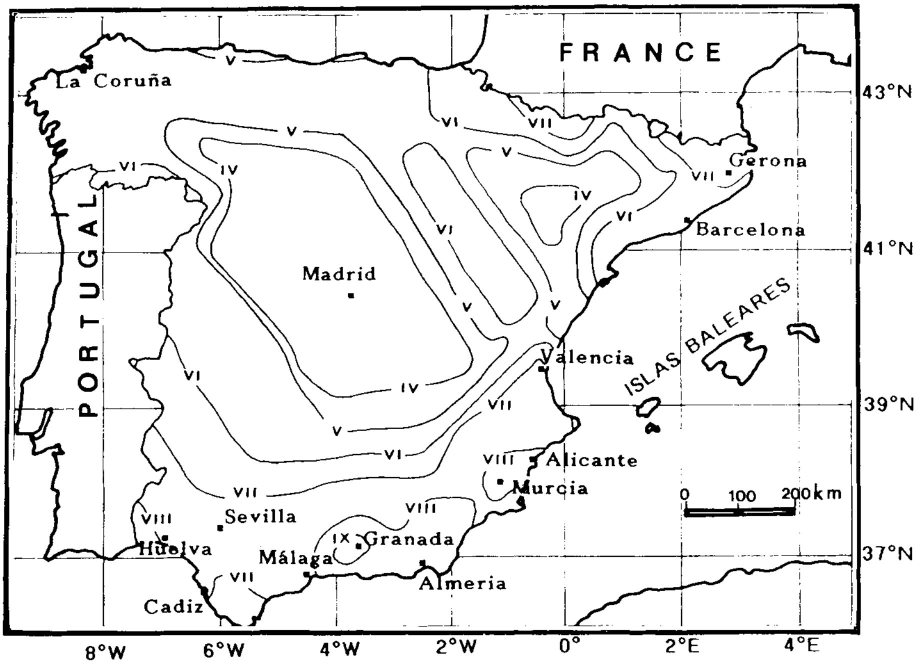

Fig.18.3. Seismic hazard map of Spain for a return period of 1000 years. Isoseismal lines indicate epicentral intensities according to the Modified Mercalli scale.

Tenerife and Lanzarote, in historical time, that is, from the late fifteenth century when the islands were occupied by Castilians; the eruptions have been located along relatively well-defined rift zones (Carracedo and Rodríguez Badiola, 1992) (Fig.18.4). Two other islands, Fuerteventura and Gran Canaria, had sub-historical or prehistorical eruptions, the latter in 3000 BP, and they present moderate risks. Finally, La Gomera has shown no activity during the Quaternary and is considered to be a very low-risk area.

In general, volcanic eruptions in the Canaries are not very dangerous since they usually consist of emissions of low-viscosity, low-explosivity alkaline basaltic magma. There are, however, four other types of hazard associated with volcanism here:

1) There can be eruption of large volumes of lava, as in the case of the 1730-36 eruption in Lanzarote when 3 to 5km^3 of volcanic products were released, covering 23 per cent of the island (Carracedo and Rodríguez Badiola, 1992; see Fig.18.4);

2) Some eruptions occur near the sea, with the danger from hydromagmatic activity: Pleistocene examples of this are known in Tenerife, La Palma, Hierro and Lanzarote;

3) There is potential risk of renewed activity of the Teide-Pico Viejo salic stratovolcano, "heir" to the large Cañadas structure whose activity began some 2 million years ago (Ancochea *et al.*, 1990), and which has been active during at least the last 160 000 years

until the fifteenth century. Recent studies, however, suggest that its magmatic chamber is not active at present.

4) Another possible hazard derives from the possibility of large landslides owing to the accumulation of volcanic materials and the stresses caused by dyke intrusion along rift zones. Several large calderas and depressions which formed in some of the islands during the Quaternary are the result of this process (Ancochea *et al.*, 1990; Navarro and Coello, 1989).

Although the frequency of volcanic events is not high (a total of 15 eruptions since 1430) and they are not normally violent, the high population density of the archipelago with more than 1.6 million inhabitants and over 5 million tourists per year makes the potential risks high.

Several institutions are presently involved in programmes related to the assessment and mitigation of volcanic hazards in the Canaries, using a variety of techniques. The Centro Geofísico de Canarias of the National Geographical Institute has a seismic

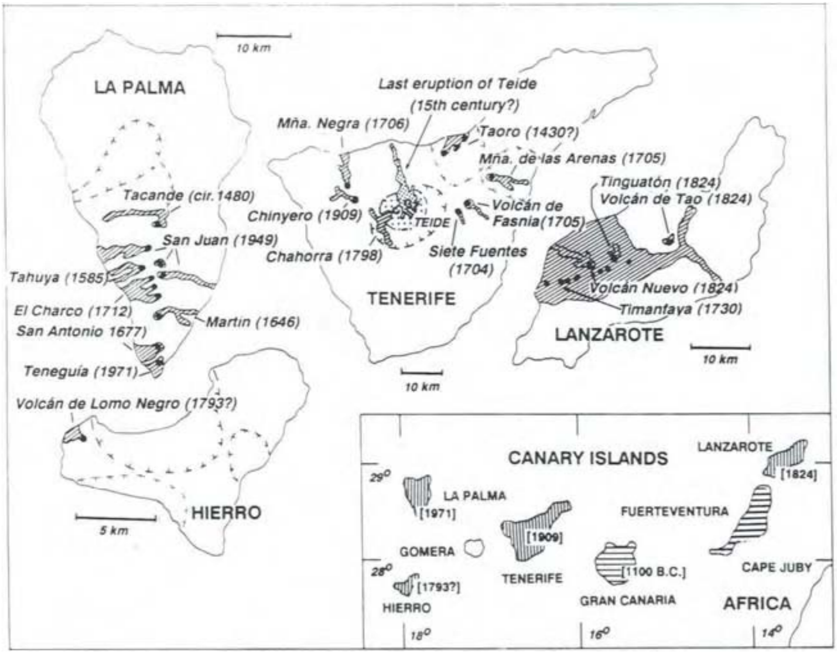

Fig.18.4. The distribution of historical eruptions in the Canary Islands. On the inset: vertical shading shows islands with historical eruptions; horizontal shading indicates islands with prehistorical activity; blank - no Quaternary activity. On the main part of the map, shading indicates areas of volcanic activity with corresponding dates; the caldera-like structures formed by large landslides are shown for Hierro, La Palma and Tenerife.

network with telemetric stations in nearly all the islands (Mezcua *et al.*, 1990); another network is being installed by the Estación Volcanológica de Canarias (CSIC) and the Departamento de Edafología y Geología of the University of La Laguna, with fixed and portable stations in the islands of Tenerife, Gran Canaria, La Palma, Hierro and Lanzarote (García Fernández *et al.*, 1988, 1989). The Museo Nacional de Ciencias Naturales (CSIC) has portable seismic stations specifically designed for volcano surveillance.

Other techniques employed include studies of geomagnetism and palaeomagnetism, magnetotelluric methods, geochemical studies of volcanic fluids, thermometry, ground deformation measurements, gravimetry, geochronology and mathematical modelling (Ortiz *et al.*, 1986; Sevilla *et al.*, 1987a, b).

Hazard zone maps have been compiled for the islands of Tenerife and Lanzarote (Araña, 1989; Carracedo *et al.*, 1990; Soler and Carracedo, 1988). Civil defence plans have been prepared in cooperation with the Civil Protection Service and the Instituto Tecnológico Geominero, and guidelines for action in the case of a volcanic crisis have been published (Araña *et al.*, 1989).

Current research programmes include studies on the instability of calderas (Museo Nacional de Ciencias Naturales, CSIC), the application of geodetic and gravimetric surveys (Instituto de Astronomía y Geodesia, CSIC and Universidad Complutense de Madrid); the development of historical eruptions (Estación Volcanológica de Canarias, CSIC); and the geochronology of volcanic activity (CSIC, Universidad Complutense de Madrid, University of La Laguna and University of Cantabria). A programme for the evaluation and mitigation of volcanic hazards in the archipelago is currently in progress (Estación Volcanológica de Canarias, CSIC, and the Consejería de Política Territorial, Gobierno de Canarias). Cooperative links for these and other projects have been established with the Consejo Nacional de Investigaciones Científicas y Técnicas of Argentina, the Consejo Nacional de Ciencia y Tecnología of Mexico, the Consiglio Nazionale della Ricerca of Italy, and the University of Clermont Ferrand, France. Geothermal research in Lanzarote is being carried out within the JOULE programme of the European Community. Especially important will be the future European Programme of Volcanological Research, part of the ENVIRONMENT programme and the European Science Foundation network on Volcanology, in which the Teide will be one of the six "laboratory volcanoes" selected for study in Europe.

4. Floods

With estimated losses of 28.2 x 10^9 U.S.dollars for the period 1986-2016 (Ayala *et al.*, 1987), floods are clearly the main natural cause of damage to property and loss of life in Spain. As Table 18.1 shows, the likely death toll from floods is far higher than that expected from any other form of geomorphological hazard (Martínez Goytre *et al.*, 1987a). Data on deaths caused by important floods in the period 1940-90 are presented in Table 18.2.

Table 18.2. Main floods in Spain between 1940 and 1990

Date	Location	Number of deaths
1940	Gerona	90
Nov.1957	Valencia	86
Jan.1959	Zamora	150
Sept.1962	Barcelona	973
July 1965	Cáceres	47
Sept.1971	Catalonia	<400
Oct.1973	South-east	300
July 1979	Ciudad Real	22
Oct.1982	South-east	38
Nov.1982	Pyrenees	30
Aug.1983	Basque Country	39
Oct.1987	South-east	7

Flooding is particularly serious in the Mediterranean region where intense rainstorms are frequent, especially during the months of September to November. Precipitation of 500-600mm in 48-72 hours, with peaks of 150mm/hour, has been recorded. These downpours provoke flash floods and cause considerable damage, particularly along "ramblas" (intermittent river courses) where inadequate land-use planning has failed to prevent human occupation of hazardous areas and where river-flow regulation works are often lacking.

The rainstorms in the southern part of the Pyrenees, where floods are also frequent, have similar characteristics (Comisión Nacional de Protección Civil, 1983; Corominas, 1985; Instituto Geológico y Minero de España (IGME), 1985). However, thicker vegetation cover, greater drainage densities and the existence of more river regulation works have made the problem less acute. In the Cantabrian region, rivers are short, with narrow valleys and lower-order drainage basins; here, floodplains have frequently been settled historically owing to the scarcity of flat land, and consequently floods can cause serious damage (IGME, 1984b).

In the large river basins such as the Ebro, Tagus (Tajo), Duero and Guadiana, floods are produced by the gradual rise of river levels after prolonged periods of rain, with resulting bank overflow. However, these rivers are nowadays regulated to a very great extent and floods today are relatively rare.

Figure 18.5 shows the distribution of the 1400 "conflict" sites in Spain where damage to property and/or loss of life by flooding has occurred. One half of these sites are in the Mediterranean and Pyrenean regions and 21 per cent in the Cantabrian region (Comisión Nacional de Protección Civil / Comisión Técnica de Inundaciones, 1983, 1984). Human activities such as deforestation, inadequate agricultural and other types of erosion-inducing practices, settlement in flood-prone areas, extraction of aggregates and construction works hindering flow in river channels, have all increased erosion hazards and risks (Garzón *et al.*, 1990; Martínez-Goytre *et al.*, 1987b; Trilla *et al.*, 1983).

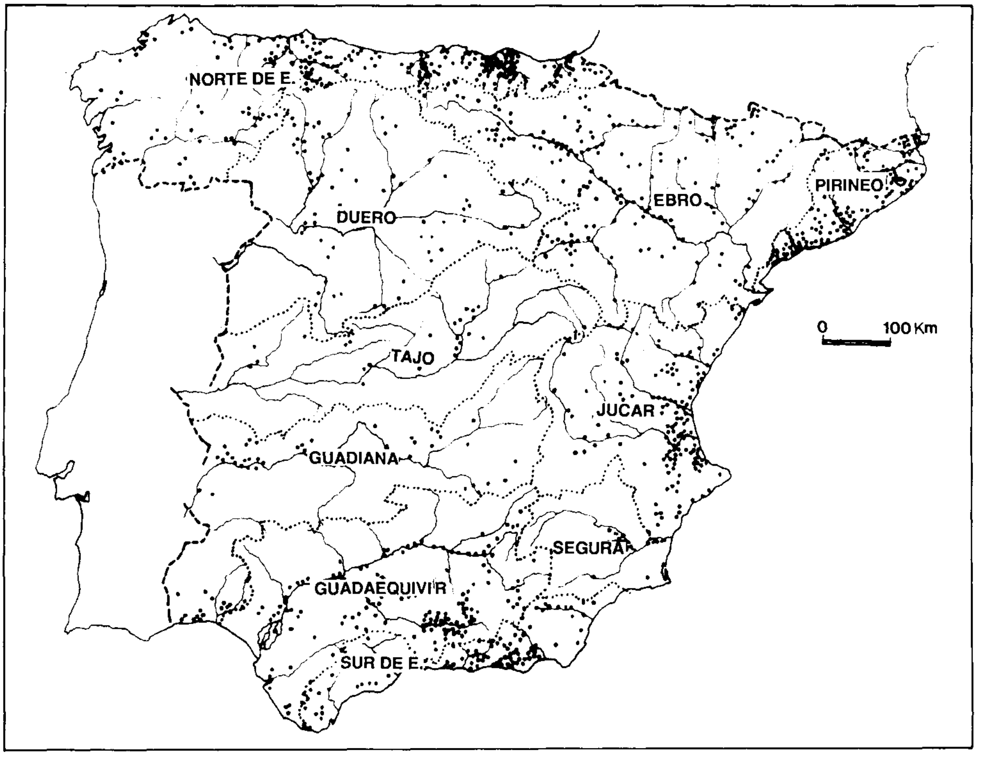

Fig.18.5. The map shows "conflict" flood sites in Spain where there has been damage to property, injury and/or loss of life. Major watersheds are marked by dotted lines (Aguilera, 1986).

Until about ten years ago, the traditional approach to flood-damage mitigation in Spain was of an engineering kind, through the construction of various corrective or control works. More recently, however, following publication of the General Report on Floods in Spain and the Map of Flood Hazard Areas (Comisión Nacional de Protección Civil / Comisión Técnica de Inundaciones, 1983), which identified 103 high-risk and 216 medium-risk areas, a preventive approach involving implementation of non-structural measures has also been undertaken. This approach includes the preparation of flood-hazard maps taking into account climatic, geomorphological, sedimentological, hydrological, land-use and historical data, at scales between 1:200 000 and 1:5000 (Cendrero *et al.*, 1986, 1987; Elízaga *et al.*, 1987; IGME, 1984a, b, 1985, 1986b, 1987a; ITGE (formerly IGME), 1989; Trilla *et al.*, 1983). Of particular interest is the application of sedimentological analyses to the identification of flood processes in the past and the elaboration of hazard maps (e.g., 1985; Elízaga *et al.*, 1987; Martínez-Goytre *et al.*, 1986-87, 1987b).

Other non-structural measures include surveillance, alert and alarm systems. The National Meteorological Institute has established a special programme, PREVIMET, which is activated mainly in the months September-November for forecasting intense rainstorms. The SAIH (Automatic System of Hydrological Information) has already been installed in the Segura, Júcar, Ebro and Pyrenean basins and is gradually being installed in others. This is a system of continuous recording of rainfall, channel flows and water levels in rivers and reservoirs, with real-time transmission of data to a control centre.

5. Accelerated erosion and desertification

With a semi-arid or even arid climate affecting more than half of its territory (Fig.18.1), an irregular rainfall régime, large areas underlain by unconsolidated clayey, silty or sandy Tertiary and Quaternary deposits, and less than 30 per cent of its area under forest, Spain is the European country that suffers most from high rates of erosion (Fig.18.6). Human activities such as mining, construction or unsuitable agricultural, forestry or grazing practices have accentuated the process (Val, 1990). Rapid or accelerated erosion has been estimated to be the second most serious geomorphological hazard in the country, after flooding, with expected losses for the period 1986-2016 of 8.7 x 10^9 U.S.dollars (Ayala *et al.*, 1987; see Soil erosion, Table 18.1).

Reviews of the incidence of erosion in Spain have been presented by Gutiérrez and Peña (1988), ITGE (1990), Sala and Gallart (1988) and Val (1990). These studies can be grouped into three categories: 1) assessment of present and/or potential erosion and mapping of erosion hazards; 2) analysis of erosion in relation to various types of land use; and 3) basic studies on the physical, chemical and biological processes associated with erosion:

1) Mapping of erosion hazards has been carried out using parametric or empirical methods, such as the Universal Soil Loss Equation, observation of present processes and landforms, and extrapolation from field measurements. Examples of small-scale maps (1:200 000 to 1:500 000) are the nation-wide surveys by the Instituto de Conservación de la Naturaleza (ICONA)(1987), and the maps of the provinces of Murcia and Almería (ICONA, 1982), Valencia (Cendrero *et al.*, 1986), and Navarra (Instituto del Suelo y Concentración Parcelaria de Navarra ISCPN/ITGE, 1990). An example of large-scale mapping is that of Sanroque *et al.* (1984) at 1:50 000/1:25 000. Also noteworthy is the map of the R factor in the Universal Soil Loss Equation and the climatic aggressivity index of Fournier prepared for the whole of Spain (ICONA, 1988).

2) The second category includes studies of the relationships between accelerated erosion and a variety of human activities such as mining (Nicolau and Puigdefábregas, 1990) and agriculture (García Ruiz *et al.*, 1986; Marqués and Roca, 1984). Other erosion-related factors such as fires (Soler and Sala, 1990) and floods (Rubio *et al.*, 1983) have also been analysed. Another approach utilises studies of sedimentation in reservoirs through bathymetric surveys.

3) Basic studies include such aspects as the influence of Holocene climatic variations on erosion (Fumanal and Calvo, 1981); the role of neotectonics in badland formation;

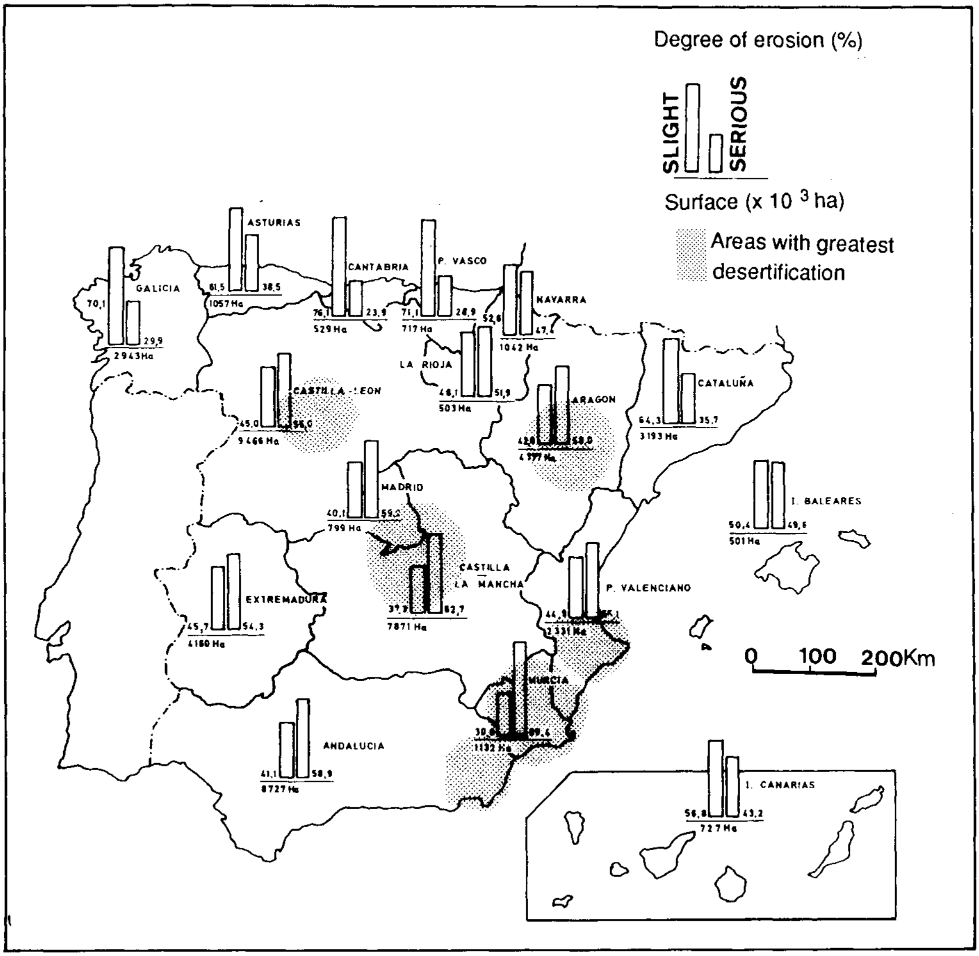

Fig.18.6. Soil erosion in the various regions of Spain. Bar graphs show percentage of area in each region affected by slight or serious erosion.

and the consequences of deforestation in historical times (Burillo *et al.*, 1981). Work on present-day processes is being carried out mainly in semi-arid and arid environments using various field techniques. Inbar (1989) has compared erosion rates in different Mediterranean environments including Spain. Badlands have received special attention and have been studied, among others, by Balasch *et al.*(1988) and Gutiérrez *et al.*(1988).

Other studies have been carried out using a variety of field and laboratory tests. Specific studies have been undertaken on the relationships between infiltration and erosion (López Bermúdez and Thornes, 1986), on simulations of solid transport and hydrological response (Llorens and Gallart, 1990), and on tests of the applicability of the Universal Soil Loss Equation (González del Tánago *et al.*, 1990). Some work has also been carried out on the variability of overland-flow erosion rates in the Mediterranean environment under a matorral cover (Romero *et al.*, 1988).

Finally, the two main programmes of international co-operation in erosion studies are: 1) the CORINE soil erosion project, for the preparation of a European small-scale erosion map within the CORINE programme of the European Community, and 2) the LUCDEME (Spanish acronym for the "fight against desertification and erosion in the Mediterranean") project. The former is coordinated by the Dirección General de Política Ambiental and the latter by the ICONA. Many groups, both from universities and from other institutions, are working within these programmes.

6. Mass movements

Because of the geological, geomorphological and climatic conditions (Fig.18.1), various types of mass movement constitute the third most serious geomorphological hazard in Spain, with expected losses for 1986-2016 estimated by Ayala *et al.*(1987) to reach 7.6 x 10^9 U.S.dollars. Some historical landslides have attained massive proportions (Table 18.3). The main regions affected are, not unexpectedly, the Alpine mountain chains with their pronounced relief, high rainfall, and many areas with unstable clays; but also significant in terms of slope failures are the dissected tabular strata in Cenozoic basins, also with abundant clays (Fig.18.7).

In the high mountain areas subject to glaciation during the Quaternary, decompression of valley sides after deglaciation has triggered numerous large landslides (Bordonau and Vilaplana, 1986; Corominas, 1990), but this type of process seems to be no longer active. Periglacial conditions, however, especially in the Pyrenees and in the Cantabrian mountains, produce gelifluction, solifluction and block streams, as well as superficial landslides affecting morainic deposits.

The most representative morphoclimatic environment typical of much of Spain consists of moderate altitudes with irregular rainfall, together with intense storms towards the end of summer and in autumn. These rainstorms generate many superficial landslides, flows, planar slides and rockfalls, most commonly only a few cubic metres in volume individually and affecting the regolith and clay-silt formations, mostly on slopes of 30°-40°(Gallart and Clotet, 1988).

Table 18.3. Some catastrophic mass movements in Spain

Location	Date	Type of movement	Damage	Volume (m^3)
Alcoy, Alicante	Dec.1620	-	City partly destroyed, earthquake triggered	-
Inza, Navarra	Dec.1714 - Apr.1715	Mudflow	Village destroyed	10^6
Biniarroi, Mallorca	Mar.1721	Rotational slide	-	-
Corbera, Valencia	Nov.1783	-	-	-
Azagra, Navarra	July 1874	Rockfall	91 deaths	-
Puigcercós, Lleida	Jan.1882	Translational slide	Village partly destroyed	$3x10^5$
Bono, Lleida	Oct.1937	Debris avalanche	River dammed	10^5
Rocabruna, Gerona	Oct.1940	Debris flow	6 deaths	-
Rosiana, Gran Canaria	Feb.1956	Translational slide	Village destroyed	$5x10^5$
Puebla de Arenosa, Castellón	Oct.1957	Earthflow	Cracks in buildings	-
Senet, Lleida	Aug.1963	Debris avalanche	River dammed	$5x10^4$
Benasque, Huesca	Aug.1963	Debris avalanche	Road destroyed	-
Alcoy, Alicante	Dec.1964	Rotational slide	Buildings affected	-
Tudela de Veguin, Asturias	1975	Earthflow	Cracks in buildings	$9x10^5$
Carege, Lleida	Nov.1982	Rotational slide	Road & bridge destroyed	-
La Guingueta, Lleida	Nov.1982	Debris avalanche	Village isolated	-
Capdella, Lleida	Nov.1982	Debris avalanche	3 deaths	-
Pont de Bar, Lleida	Nov.1982	Translational & complex slide	Village & road destroyed	10^7
La Coma, Lleida	Nov.1982	Mudflow	-	$2.5x10^5$
Gósol, Lleida	Nov.1982	Translational slide & mudflow	-	10^6
Sta Cruz de Moya, Cuenca	Apr.1984	Translational slide	-	10^5
Olivares, Granada	Apr.1986	Mudflow	Village affected	$3.6x10^6$

According to Corominas (1989), the chief stratigraphical units in Spain which are prone to slope failure and instability are:

- Dark, deformed Carboniferous and Silurian shales, which show frequent rotational slides and flows in the Pyrenees and the Cantabrian mountains;

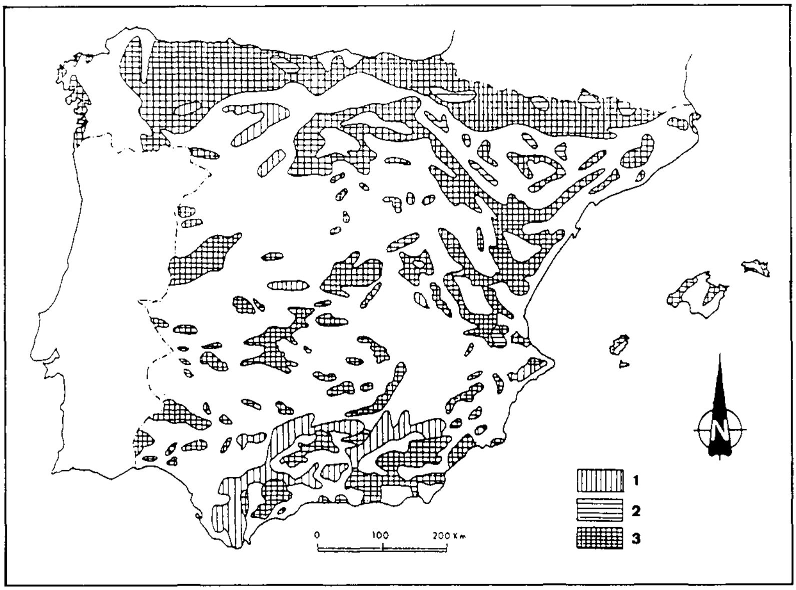

Fig.18.7. Main areas subject to mass movement in Spain. 1 - mainly landslides; 2 - mainly rockfalls; 3 - landslides and rockfalls (IGME, 1987b)

- Keuper argillites and evaporites, with many flows and rotational slides which are sometimes transformed into larger flows;
- Mesozoic marly formations and Palaeozoic schists of the Nevado-Filábrides and Alpujárrides Complex, in the Betic region, particularly at the contacts between marble and schist units;
- Claystones and siltstones of the Wealden and other Cretaceous argillaceous formations. They suffer from a variety of movements, mostly rotational and translational slides, often turning into flows. There are examples in the Cantabrian mountains, the Valencia region and Andalusia;
- The thick flysch sequences, mainly Eocene, with large and frequent rotational and translational slides and flows, such as those of the Basque coast or in the Bay of Cádiz;
- The clayey-silty-sandy Miocene deposits, sometimes with evaporites, of the Tertiary depressions in the central part of the country, showing solifluction, rotational slides, flows and toppling failures, usually not very large;
- Quaternary, unconsolidated deposits, such as Pleistocene alluvium dissected by present drainage networks, and till deposits in mountain areas.

It is also worth mentioning the large translational slides along bedding planes, sometimes with angles less than 20°, that take place in many parts of the sierras bordering the Pyrenees, the Cantabrian, Iberian and Betic mountain chains.

Possibly the greatest potential landslide hazard in the country, although not very probable, would be the sudden displacement of very large wedges of volcanic material in the Canary Islands, like the events that occurred during the Pleistocene (as mentioned in section 3: Ancochea *et al.*, 1990; Navarro and Coello, 1989).

Mass movement studies presently being carried out can be grouped into two main categories: 1) mapping of processes, hazards and risks; 2) detailed studies of specific aspects of mass movement. Investigations have been conducted chiefly by the Servicio Geológico de Obras Públicas and the Instituto Tecnológico Geominero de España (ITGE), as well as by many groups in universities and the Higher Council for Scientific Research (CSIC).

Maps have been compiled at scales between 1:1 000 000 for the whole country, and 1:5000 for municipal areas. Examples of small-scale maps are the national map at 1: 1 000 000 (IGME, 1987b), the 1:400 000 maps for Andalusia, Castille and León, and the 1:200 000 map for the province of Madrid (IGME, 1986a). From 1975 onwards, the Servicio Geológico de Obras Públicas published a series of 1:100 000 maps showing problem areas, geological formations liable to experience mass movement, types of movement and stability angles. Geological hazard maps including landslides, at the 1:25 000 scale, have been compiled for several urban areas (IGME, 1984a).

Maps at scales greater than 1:10 000 have been published for various cities, and also for municipal areas in different parts of the country, such as the 1:5000 maps for the Basque country (Cendrero *et al.*, 1987; González *et al.*, 1992).

In general, maps have been made using a geomorphological approach, based on identifying and classifying different types of movement, but in other cases a statistical approach, based on correlating the controlling factors with the observed movements, has been adopted (Cendrero *et al.*, 1987; Duque *et al.*, 1990). Geographical Information Systems have also been used (Chacón *et al.*, 1992).

Detailed specific studies of mass movements cover a wide variety of aspects, such as the analysis of controlling and triggering factors, failure mechanisms and types of movement, local studies for the correction or prevention of failures on both natural and artificial slopes, economic assessments of damage and costs of corrective measures, and national inventories of movements (Chacón and López, 1988).

7. Swelling clays

Damage caused by swelling clays has been estimated at about 1000 million U.S. dollars for the period 1986-2016 (Ayala *et al.*, 1987; Table 18.1). About one-third of the geological formations in Spain contain swelling clays, and two-thirds of the territory has climatic conditions that favour changes of volume (Salinas, 1988). Figure 18.1 shows the values of Thornthwaite's humidity index (Justo and Cuéllar, 1972). Areas where the index is negative and seasonal moisture contrasts greater, thus promoting expansion and contraction, cover over 300 000km^2. Superficial and bedrock formations containing swelling clays occupy 157 000km^2. Table 18.4 gives data on the distribution of swelling

Table 18.4. Extent of geological formations (km^2) with hazards caused by expansive clays, in various regions of Spain (Ayala *et al.*, 1988)

	Degree of hazard resulting from swelling/shrinking			
Region	Nil-low	low - moderate	moderate - high	high - very high
Cantabrian Region	778	4 380	0	0
Ebro Basin	2 460	18 104	8 704	0
Extremadura	130	8 491	4 941	0
Northern Plateau	2 585	29 170	7 720	0
Southern Plateau	4 060	22 004	5 200	1 835
South-east	988	14 491	1 970	659
Andalusia	1 562	12 045	7 512	9 544
Totals:	12 563	108 685	36 047	12 038

clays in different regions. The greatest hazards are presented by the Neogene clays in the Ebro and Guadalquivir basins, in the south-east region and in the central Meseta, as well as by the Keuper clays in the Mesozoic folded areas.

General studies on expansive soils in Spain include the map on a scale of 1:1 000 000 by Ayala *et al.*(1986) and the geotechnical maps on scales from 1:100 000 to 1:200 000 that are published for several regions by the IGME (1976).

More specific studies deal with the analysis of shrinking and swelling processes and their controlling factors, identification of expansive clays, determination of foundation conditions and tests of corrective techniques (Salinas and Oteo, 1989). Most of these studies have been carried out by or in connection with the Centro de Estudios y Experimentación de Obras Públicas (CEDEX).

8. Avalanches

The main mountain areas in Spain - the Pyrenean, Cantabrian, Iberian, Central and Betic Ranges - have altitudes greater than 1500m and experience snowfalls on more than 90 days each year. In many of these areas, there has been intensive touristic development in the last few decades, with the construction of ski facilities, hotels and roads, and the consequent exposure of more and more people to the risks of avalanches. There are 25 winter sports stations in the country that receive a total of more than 3.5 million visitors each year. In the period 1975-91, 77 deaths occurred as a result of avalanches in mountain areas.

There is no national programme for the assessment and mitigation of avalanche hazards in Spain, such as those in the Alps, but some measures have been undertaken. In the central Pyrenees, an inventory of 323 avalanche tracks has been compiled (Muñoz, 1988) and defence works have been built in those areas with the highest risk. Some nivo-meteorological stations have been installed, mainly for the assessment of water resources from snow, but they also provide valuable information for avalanche prediction (Ministerio de Obras Públicas y Urbanismo, 1988). These stations are in the Pyrenees but will also be installed in the Cantabrian Range and in the Sierra Nevada.

Other studies cover the eastern Pyrenees, where a preventive system has been designed including real-time transmission of snow data and the setting-up of a public information campaign (Furdada *et al.*, 1990). In the Sierra Nevada, a 1:50 000 hazard map has been compiled, showing areas at risk on the basis of relevant geomorphological and climatological factors such as altitude, slope, orientation, landform, prevailing winds, precipitation and solar radiation (Durán *et al.*, 1992).

9. Karstic hazards

Spain has about 100 000km^2 of carbonate terrains and >32 000 km^2 underlain by evaporites (Fig.18.8), both with large karst systems. There are over 10 000 karstic cavities, including eight with depths greater than 1km and over 100 more than 3km long. The regions with the greatest development of karst are the Balearic Islands, the Pyrenees, and the Cantabrian, Iberian and Betic Ranges. Many recent cases of karst-related problems have been documented (Fig.18.8), mainly on Triassic and Neogene gypsum and Mesozoic carbonate formations.

General studies related to karst hazards include the map of karst in Spain (scale 1: 1 000 000; IGME, 1986c), an inventory of large cavities (Puch, 1987), a monograph on karst in Spain by Durán and López-Martínez (1989), and a synthesis on karst problems in gypsum areas (Durán and Val, 1984). Other, regional studies have been carried out, for instance on the Neogene gypsum formations of the Ebro basin (Benito and Gutiérrez, 1987; Gutiérrez *et al.*, 1985), and on the Triassic gypsum of the Betic Cordillera (Durán and Burillo, 1986).

Most studies on karst hazards include the preparation of maps based on data about lithology, structure, geomorphology, hydrogeology, speleology and historical events. Recently, high-resolution geophysical methods, such as detailed gravity surveys, have also been used.

10. Coastal hazards

Spain has more than 6600km of coastline, including the Balearic and Canary Islands, of which 58% consists of rocky cliffs, 30% of fine- to coarse-grained beach sediments, 1% of very fine-grained sediments and 1% estuaries; the remaining 10% comprises

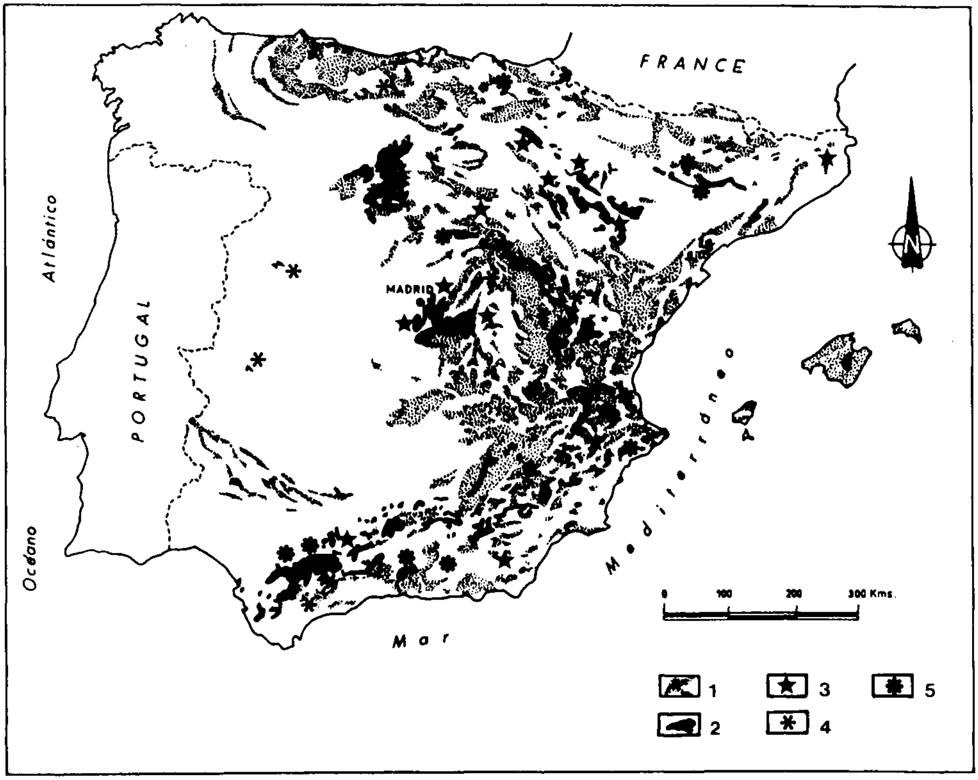

Fig.18.8. Distribution of karst in Spain. 1 - carbonate rocks; 2 - evaporites; 3 - sites of recent collapse in evaporites; 4 - sites of recent collapse in carbonates; 5 - dams with hydro-geological and/or geotechnical problems related to the presence of karst (Durán and López Martínez, 1989)

artificial coastlines. About 80% of the coast is stable or nearly so, whereas nearly 10% suffers from erosion problems (Quélenec *et al.*, 1987). More than 35% of the 38 million inhabitants of Spain live within 5km of the sea.

Coastal erosion affects the coasts of the Mediterranean, the coast between Gibraltar and Portugal and, to a lesser extent, the coast of the Bay of Biscay. Of the 638km of coast with erosion problems, 472km consist of sandy beaches. Erosion problems are likely to increase if the observed trends of sea-level change continue (Zazo *et al.*, 1990).

Damage caused by coastal erosion during the period 1986-2016 is predicted to reach 3.21×10^9 U.S. dollars (Table 18.1; Ayala *et al.*. 1987). Further rise of sea level would produce a corresponding increase in damage, perhaps even reaching 5×10^9 U.S. dollars for the eastern part of the Bay of Biscay alone (Rivas and Cendrero, 1991).

Tsunamis have also affected some sectors of the Spanish coast in the past, although they do not represent an important hazard. In the worst possible situation, estimated costs of damage could reach 3.9 billion U.S. dollars, 1986-2016 (Ayala *et al.*, 1987).

Research on coastal hazards and related problems is being carried out by different groups, many connected with the working group on coastal changes, related to Project no. 274 of the International Geological Correlation Project (Coastal evolution in the Quaternary), and with the Commission on Shorelines (International Quaternary Association). The main lines of work are: compilation of thematic and hazard maps, coastal sediment models, faunal changes and geochronology. Two examples of monographs published are by Dabrio *et al.* (1990: fan-delta deposits in south-east Spain) and by Díaz del Olmo and Rodríguez Vidal (1989: the Quaternary of western Andalusia).

Measures to combat erosion and other coastal problems are undertaken by the Ministry of Public Works and Transport, within the overall framework of a programme designed to mitigate erosion at the most critical sites.

11. Geomorphological hazards in Andorra

Andorra is a small principality of 468km^2 on the southern slope of the eastern Pyrenees; it lies almost entirely above 1000m (75 per cent above 1800m). It has a typical mountain climate with abundant snow during the winter, but also experiences a Mediterranean climatic influence with strong autumn rainfall. Arising from this background, the main hazards are floods, mass movements and avalanches. Floods, mainly related to the river Envalira and with a periodicity of 30-40 years, cause great damage because of the concentration of settlement along the scarce narrow strips of flat land along the valley floors. Nival and periglacial conditions over most of the country favour creep, solifluction, gelifluction and block movement. Large landslides and rockfalls occurred in many valleys in the aftermath of deglaciation, and have also been encouraged by the plasticity of the highly deformed Silurian shales (Corominas, 1990).

Mapping of avalanche hazards at the 1:10 000 scale has been completed for about two-thirds of the country (Becat, 1988), and similarly for flood and landslide hazards at 1:25 000 (Corominas, 1990-91). Other measures include a plan for flood control along the river Envalira, with an estimated budget of 25 million U.S. dollars, including river channel regulation works in all urban areas and wherever roads are affected. In the case of landslides, only a few local attempts have been made to overcome specific problems.

13. Conclusion

Of the countries of Europe, Spain is certainly among those most affected by geological and geomorphological hazards. Practically the whole of the territory is prone to some kind of geomorphological hazard (Fig.18.9; Table 18.5) but it is in the eastern and southern coastal strips that the risks are greatest. In Andalusia, expected losses for the period 1986-2016 range from 0.13 to 0.35 million U.S.dollars/km^2, and from 1700 to 4800 dollars per person. The figures for southern Castille are 0.02 million dollars/km^2 and 1000 dollars per person. For other regions, the expected losses lie somewhere in between these two extremes.

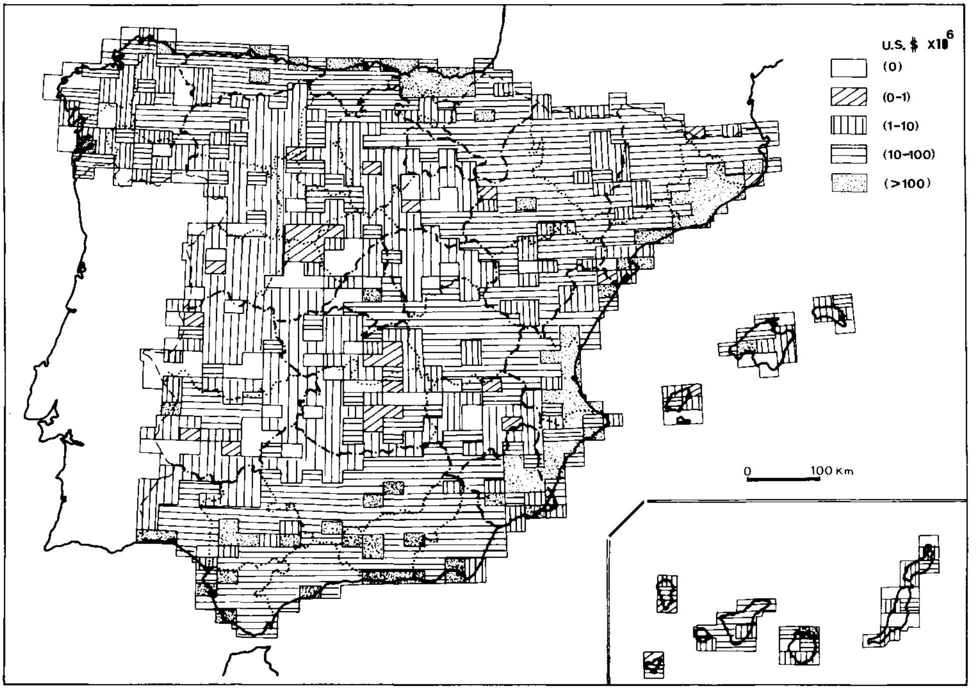

Fig.18.9. Expected losses from geological and geomorphological hazards in Spain for the 30-year period 1986-2016 (modified from Ayala *et al.*, 1987)

The traditional approach to natural hazard mitigation was based, until the late 1970s, on the construction of engineering works at specific points of danger or conflict. Since then, a more comprehensive, preventive approach has also been adopted. This includes the compilation of hazard-zone maps and maps of individual types of risk, both small-scale (at the national level) and large-scale (at the local level). Surveillance, alert and alarm systems have been installed for the prediction of such events as volcanic eruptions, earthquakes, floods and avalanches, any of which can cause serious loss of life.

The coverage of hazard mapping is still far from complete or adequate, and much work remains to be done, especially in detail. So far, too, there has been considerable

Table 18.5. Some important geological and geomorphological events in Spain (Ayala *et al.*, 1987)

Hazard	Year	Location	Damage	No. of deaths
Earthquakes	1428	Olot	Several villages destroyed	500
	1504	Carmona	Damage in several localities, $>7.5x10^6$ ptas, "maravedíes"	100
	1522	Almería	Great destruction	Many
	1680	Málaga	>10% of Málaga destroyed	Many
	1829	Torrevieja	Damage $>8.5x10^6$ ptas, "reales de vellón"	Many
	1884	Arenas del Rey	>1000 buildings destroyed; damage $>10x10^6$ ptas	900
Tsunamis	1755	Cádiz	Great damage along coast; Conil destroyed; Cádiz damaged	1000
Volcanoes	1430 - 1971	Canary Islands (15 eruptions)	Important damage in several localities	Some
Floods	1651	Murcia	Severe	1000
	1802	Lorca	Town destroyed	700
	1874	Catalonia	>700 houses destroyed	600
	1879	Murcia	Severe	800
	1957	Valencia	>300 buildings destroyed; damage $>10\ 000x10^6$ ptas	82
	1962	Catalonia	5000 houses destroyed; losses $>2700x10^6$ ptas	1000
	1971	Catalonia	Damage $>7000x10^6$ ptas	400
	1973	South-east	Severe damage over wide areas	300
	1982	South-east	Losses of $300\ 000x10^6$ ptas	38
	1983	Basque Country and Cantabria	Damage $>150\ 000x10^6$ ptas	40
Landslides	1874	Azagra, Navarra	Village destroyed	100
	1986	Olivares, Granada	Losses of $1000x10^6$ ptas	-

Note: In 1992, 100 pesetas were approximately equal to 1 U.S. dollar. Economic losses are given in actual figures for the year of the event, without allowance for changes in monetary values.

diversity in the methods used for risk assessment and for the cartographic representation of natural hazards. An urgent need is to establish common, generally accepted methodologies and criteria, based on indicators defined as clearly as possible, as well as to standardise map legends and scales for different planning levels.

One of the main problems for the mitigation of geomorphological hazards in Spain is the lack of an appropriate regulatory framework for the incorporation of natural hazard assessments into land-use planning and management at the macro-, meso- and micro-planning levels. Information programmes for the general public also need to be considerably expanded.

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The following abbreviations are used, here and in the text:

CEDEX: Centro de Estudios y Experimentación de Obras Públicas (Centre for Studies and Experimentation in Civil Engineering)
CNR: Consiglio Nazionale della Ricerca (Italy) (National Research Council of Italy)
CONACIT: Consejo Nacional de Ciencia y Tecnología (Mexico) (National Council for Science and Technology)
CONICET: Consejo Nacional de Investigaciones Científicas y Técnicas (Argentina) (National Council for Scientific and Technical Research)
CSIC: Consejo Superior de Investigaciones Científicas (Higher Council for Scientific Research)
DGMA: Dirección General de Medio Ambiente (General Directorate for the Environment)
ENRESA: Empresa Nacional de Residuos, S.A. (National Waste Processing Company Ltd)
ICONA: Instituto de Conservación de la Naturaleza (Institute for Nature Conservation)
IGC: Instituto Geográfico y Catastral (Geographical and Cadastral Institute)
IGME: Instituto Geológico y Minero de España (Mining and Geological Institute of Spain)
INGEMISA: Investigaciones Geológicas y Mineras, S.A. (Mining and Geological Investigations, Ltd)
IGN: Instituto Geográfico Nacional (formerly IGC) (National Geographical Institute)
INM: Instituto Nacional de Meteorología (National Meteorological Institute)
ISCPN: Instituto del Suelo y Concentración Parcelaria de Navarra (Institute for Soil and Agricultural Planning in Navarra)
ITGE: Instituto Tecnológico Geominero de España (formerly IGME) (Technological Geomining Institute of Spain)
MOPU: Ministerio de Obras Públicas y Urbanismo (Ministry of Public Works and Urban Planning)
UCM: Universidad Complutense de Madrid (Complutense University of Madrid)

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SWEDEN

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1. Introduction

Geomorphological hazards are not very often reported from Sweden. The reasons are mostly obvious, but a summary is called for. Present-day geomorphological processes, slow or fast, are almost exclusively connected with glacial transformation, resulting in steepening of rock slopes and the deposition of glacial sediments.

Sweden is part of the Baltic Shield, stabilised long ago. Present plate boundaries are distant and earthquakes are of low magnitude. The country is dominated by solid Precambrian granites and gneisses, but Caledonian rocks such as amphibolites, mica-schists and quartzites are also resistant. Less resistant rocks, Cambro-Silurian and younger, are only found locally, mainly in the south. Preglacial regolith has generally been removed by ice: the few exceptions are small, compared with the extent of fresh bare rock.

The areas of gentle, mainly preglacial relief in Sweden occupy a median position compared with Norway and Finland, the former usually being much higher and steeper while the latter has an even lower amplitude of relief than Sweden. In the Precambrian areas of Sweden, true plains are frequent in the south, otherwise the landscape tends to be hilly, undulating, or consisting of inselberg plains. The hills have a relative relief of 100-200m and slope angles around 10-15 degrees in the northern highlands; these figures are reduced by one-half in the southern highlands.

Steeper rock slopes, more than 25 degrees or even near-vertical, only occur locally, more often in the north. Exceptions are the joint-valley landscapes of southern Sweden in western and eastern areas. They include long fault-line scarps, old but sometimes steepened by ice. The relative relief of the Caledonides is higher, usually 400m or more. Gentle relief is often predominant, but steep slopes are more common than in Precambrian Sweden, particularly in rocks of high metamorphic grade, in relation to certain structures (overthrusts), and in the main valleys, which are often incomplete U-shaped valleys. True U-shaped valleys like those of Norway are restricted to the highest mountain areas (Sarek, Kebnekaise and a few others). The steeper rock slopes, or at least the steepest, in Precambrian and Caledonian regions are thought to be glacial for two reasons: 1) they are usually more or less leesides in respect of ice-movement (Rudberg, 1973); 2) they are not in balance with the present climate and often in a state of slow destruction with talus slopes at the base (more frequent in the north).

Till dominates the Swedish landscape, but with varying degrees of coverage and thickness, regionally and locally, strongly influenced by ice movement, ice melting, etc., and often possessing its own range of constructional forms. In some areas, notably in the south-west and in the north-western parts of the mountains, the till cover is thin or almost absent; these areas are offshoots from the great bare rock zone in Norway (Rudberg, 1967a; for a detailed example, see sheet 4 of the Nordkalott Project 1986). Thickness figures are not generally available but could amount to a few metres in most parts of southern Sweden, a metre or so over large parts of the mountains, about 7-8m over broad areas of Precambrian northern Sweden (Rudberg, 1954; Fromm, 1965) and still more in the Härjedalen province (J.Lundqvist, 1969). In Precambrian areas, the till consists of a mixture of grain sizes ranging from clay to boulders, without vertical differentiation (unlike regolith), except when the till surface has been washed by wave action. Varieties with sand-silt as the fines are most frequent. In the Caledonides, it is hard to estimate the average composition for tills.

Less common than till but still widespread, are the young *water-transported sediments* - glacifluvial, glacial and post-glacial marine and lacustrine deposits. Thick accumulations in valleys may amount to tens of metres, even more than 100m. Beds of clay are particularly frequent in south-west Sweden, but silt is predominant in the valleys of northern Sweden.

In Sweden, the *relative resistance to erosion* of till and glacifluvial sediments, compared with undisturbed regolith from the same rocks, has never been investigated. It should be stronger for till from Precambrian rocks, perhaps equal for some glacifluvial beds, equal or lower for clay beds and much lower for silt. One difference ought to be remembered: the transition from solid rock to regolith is gradual, whereas that from bedrock to glacial/glacifluvial deposits is a sharp contact, where the rock surface is often a more or less polished stoss side. Such contacts are more frequent than on rugged lee sides. Planes of various S-surfaces may act in the same way as polished surfaces.

The *post-glacial land uplift* is of central importance for post-glacial changes and hazards. The present maximum is 0.9m/100 years on the north-west shore of the Gulf of Bothnia. Uplift since local deglaciation has amounted to nearly 300m along the Gulf of Bothnia, over 150m south of Stockholm, but around 100m at Göteborg, for example. To account for these figures, rates of uplift must have been higher in the early stages of deglaciation: Lidén (1913) suggested 10.8-14.4cm per year. The post-glacial uplift represents a high rate of neotectonic movement, which even gave rise to some faults in the otherwise stable Precambrian area of northernmost Sweden (Lagerbäck, 1977). At most, however, such events were experienced by some erratic hunter! The consequence of uplift is a steadily sinking base-level. This has caused fast river incision in the thick beds of sand, silt and clay in valleys. In all rivers, however, stronger layers were found during incision, which have isolated the upper reaches from a further sinking base-level.

As Sweden has a considerable north-south extent, the *climate* varies from a central European type to sub-Arctic, the annual mean temperature ranging from 7°C in the south to -2°C in the northernmost inhabited valleys. Precipitation is sufficient for a vegetation cover in all parts of the country, except for some small high areas with low summer temperatures or strong winds. The timber line sinks from around 900m in the south to 500-600m, or even lower, in the north. Elsewhere, forest should be the natural vegetation where it has not been cleared for agriculture or the land is not too poorly drained. The forest has a continuous mat of ground vegetation, except in a few small beech forests in the south and some planted spruce forests. Part of the annual precipitation is stored in the snow cover, lasting less than 40 days in the extreme south, 80-120 days in the lowlands of central Sweden and up to 210 days in Lapland. Snow comprises 25 per cent of the annual precipitation in the northern highlands and more than 50 per cent in a few parts of the mountains. These figures may seem low but are the result of the high proportion of the precipitation that falls in the summer months over most of the country (*Atlas of Sweden*, sheet 31-32), occasionally in heavy rain falls. Snow drifting is important in all mountain areas, leading to drifts several metres thick or, in contrast, bare patches. Snow drifting can also be severe on cultivated fields in southern Sweden.

Snow melt produces *high river discharges*, lasting longer in the main rivers of northern Sweden because of more snow and later melting in the mountains (Atlas of Sweden, sheet 37-38). Ice jams with irregularly spaced high-water stages present a local problem in some rivers (Melin, 1970), notably for parts of the Torneälven (Hjort, 1971). Flooding can occur in low-lying areas; for the main rivers, the ratio of mean high-water discharge to mean low-water is 20:1 or more for medium-size rivers in northern Sweden, but less in southern Sweden. The sizes of lake areas linked in the river systems are important.

As the definition of a hazard involves *man and his activities*, two points relevant to Sweden should be stressed. The rural land areas are sparsely populated; some areas are devoid of people. Colonisation by farmers was very late in interior northern Sweden, for example in the large Lappland area. It had its first farmers 300 years ago, but the main part was settled in the first half of the nineteenth century and some river valleys not until this century (Rudberg, 1957). The agrarian population has retreated in the last 30 years, but farming is abandoned earlier than farms. Swedish historical records are poor before the sixteenth century, but are quite good (according to international standards) after 1600, particularly as to large-scale surveys of cultivated ground.

It can thus be seen why geomorphological hazards are not often reported from Sweden. In summary, the mainly gentle relief, resistant rocks, relative resistance of the glacial tills, continuous vegetation cover and the mainly undramatic climate should be noted. On the other hand, there are locally steep glacial slopes, thick erodible and sometimes unstable sediments in the valleys, drifting snow, occasional heavy rainfall, and disturbance by man.

2. Processes and hazards on steep slopes

2.1. Rock falls and slides

Steep rock slopes occur locally in Precambrian Sweden, and most of them being glacially formed face south or south-east. Areas close to them have a favourable local climate owing to insolation and wind protection, and have quite often attracted farms, villages, suburban settlement and even small towns, now lying at the base of a rock face or talus slope. In the long term, such sites may be dangerous for rock falls or large talus boulders. Two cases will be mentioned. In Funäsdalen village in the southern part of the mountains, houses are built close to the talus slope below a steep face. A few years ago a large falling boulder failed to stop at the base of the talus and almost struck the parsonage. In another example, a rock fall from the steep fault-line scarp east of Lake Vättern, close to the town of Huskvarna, recently destroyed a nearby house.

Rock falls and slides occur in steep- or vertical-sided road cuttings. There are many examples from western Sweden, temporarily blocking roads. There is no record of loss of life yet, even in the case of a main road north of Göteborg during the early morning rush-hour when a block of several tons fell down. The road cutting here crosses S-surfaces dipping steeply towards the road.

People usually do not live at the bases of the much higher steep rock slopes in the mountains, but rock falls occasionally cause problems for lines of transport, as is well documented for the railway between Kiruna and Narvik (Rapp, 1961, p.108).

Rock falls of a special kind occur from the low plateaus of Västergötland where flat-bedded Cambro-Silurian sediments are capped by Permo-Carboniferous dolerite. The plateaus are surrounded by steep rock slopes, representing glacial lee sides and/or marine cliffs around the plateaus of Halleberg and Hunneberg, where the main parts stood below the highest post-glacial shoreline. They have near-vertical rock walls with columnar joints in their upper parts, and active, unvegetated talus slopes (Rudberg *et al.*, 1976). Most houses are at some distance from the talus base, but there is always a risk of big slides on slopes where weak rocks such as alum slate lie below hard and heavy ones. A slide occurred at the northern end of the Ålleberg plateau (Zenzén, 1929).

On the north-western side of Halleberg, there are several open joints, 50-100m long, not far from the plateau edge and parallel to it. People call them "Onda hålen" or the Evil Holes; they were reported by Rudberg *et al.*(1976) and measurements have been started to see if the joints are widening. On the south-western corner of Hunneberg, a big slide has occurred as evidenced by lower slope angles, irregular heaps of large dolerite boulders and, locally, slates standing vertically. Its age is unknown. Slides of this type are known elsewhere in Europe, described for example by Mortensen and Hövermann (1956), Mortensen (1960), Zaruba and Mencl (1969), and Pasek (1967).

2.2. Debris slides and flows

Till resting on steep slopes, especially when it contains a lot of fines, is not too thick and is situated on a smooth rock surface, may become unstable when saturated by water from rain or snow melt. The resulting debris slides and flows are reported from several places in Sweden. The first description is probably by Zenzén (1926) from a minor isolated mountain of Precambrian rock north of Lake Hornavan, northern Sweden. The flow had a length of 500-700m and is thought to have been released after prolonged heavy rain. Two more examples are briefly described by Ängeby (1947). Another, examined by Rudberg (1950), descended the hill-slope above Lake Ajaure (on the river Umeälven) on Midsummer Day, 1947, following a thunderstorm. The sketch map (Fig.19.1) was made two years later. Initiation seems to have been from four or five different slides in the tundra zone above 700m, on a relatively steep concave slope. The rock surface, revealed in all the tracks, probably acted as a slip surface. Most of the slides stopped on reaching the birch forest, but when two slides met, the combined slide continued, becoming a flow through the birch and lower spruce forest to the lake, branching out on the lower slopes and up to 100m broad. Many big tree trunks lined the track in the form of levees. The total length is about 2km. Valuable forest was destroyed and one grazing animal killed.

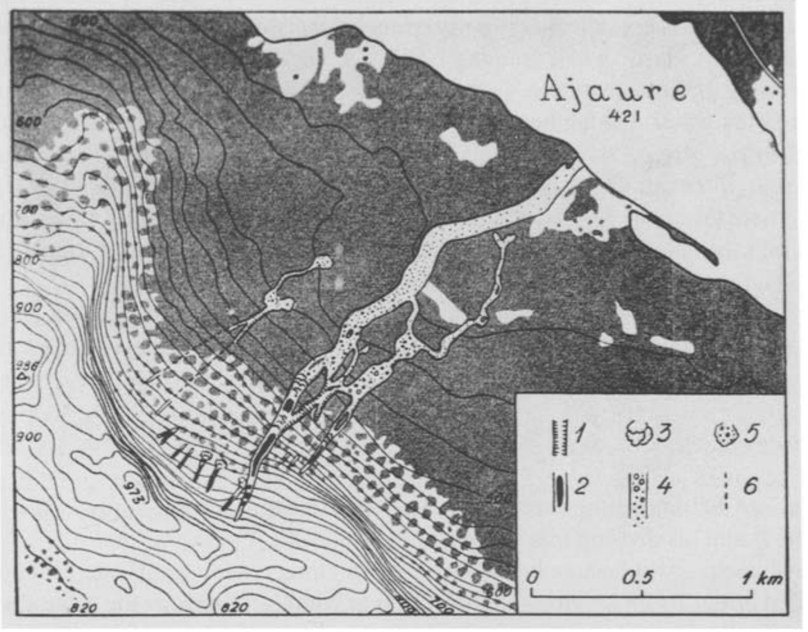

Fig.19.1. Debris slide and flow at lake Ajaure, Umeälven valley, released during a local heavy rainstorm on Midsummer's Day 1947. Sketch map made by the author 2 years later (Rudberg, 1950). The upper part is a slide, the lower, greater part a flow. 1. Eroded gully; 2. Bare rock; 3. Slide lobes; 4. Accumulation zone; 5. "Boulder delta"; 6. Interpolation. The shading indicates forest.

The spectacular geomorphological effects of heavy autumn rain, resulting in numerous bowl slides in the Kärkevagge valley, northern Sweden, in 1958 have been described by Rapp (1961). The same author (1974) reported debris slides and flows after heavy rain in Tarfala, Kebnekaise. In 1979, exceptional rainfall caused many similar mass movements in the Nissonvagge valley, some 10km from Kärkevagge. They were initially described by Rapp and Nyberg (1981) and in more detail by Nyberg (1985). The event was recorded as "by far the largest known case of rainfall-induced rapid mass movement in the Swedish mountains". The area affected by the rainstorm was about $40km^2$, and the density of flow tracks about 7 per km^2 (more in some areas); some tracks were more than 1km in length. Estimates of the recurrence interval of such events vary widely. Nyberg identified older debris flow tracks and used dendrochronology for dating. The frequency of major events, on conservative estimates, is about 6 or 7 in 2500-2600 years. As Figure 19.2B shows, fossil debris flows have been mapped from most areas of the Swedish mountains but without detailed descriptions.

Debris flows have only occasionally been witnessed in motion (see the example from Norway in Rapp, 1961). I once provoked a small flow, some tens of metres in length, when walking across a gentle, grass-covered mountain slope. The till was saturated with water and almost elastic when jumping on it. The cross-profile was convex at the peak flow and later became concave with levees at the former outer margins, containing sediment-laden water flowing between them in the end stage. Minor flows may perhaps be set off by the ground shaking induced by reindeer. Debris flows are often released in areas of thin till cover, which is stripped away down to the bedrock; the latter then acts as the slip surface, but this is not always the case. Traces of debris flows are more frequent on steep Norwegian slopes, and also on till-covered slopes in Canada (Dionne *et al.*, 1984), the relationships with bedrock being similar to those in Sweden.

Debris flows in the Swedish mountains do not appear to have ever caused loss of life, as people do not live in the dangerous areas, but with increasing summer tourism the risk is likely to increase too. Loss or damage to property has occurred in several areas.

2.3. Snow avalanches

These also belong to the mountains. The most comprehensive study is still that by Rapp (1961) and his division into three types is still valid. These are:

1. Slab avalanches, when snow layers move down along a sliding surface, which may be provided either by underlying snow of different composition or by the ground surface;
2. Avalanches in loose dry snow, often released by a block of snow falling from a snow drift at the top of a steep slope;
3. Very wet or "slush" avalanches caused by the saturation of snow with water.

The second type was the most common in the Kärkevagge investigation, but this trough valley is surrounded by particularly high and steep mountains. In the relief of the more gentle Swedish mountains, the relative importance of the first and second types is not known. All three types are initiated from heavy snow drifts, produced by re-distribution of a moderate snow cover through strong south-west to north-west winds and occurring most years in the same spots.

Slush avalanches (Fig.19.2) have recently been studied in more detail by Nyberg (1985, 1989). They are often released in minor valleys by the breaching of a snow dam

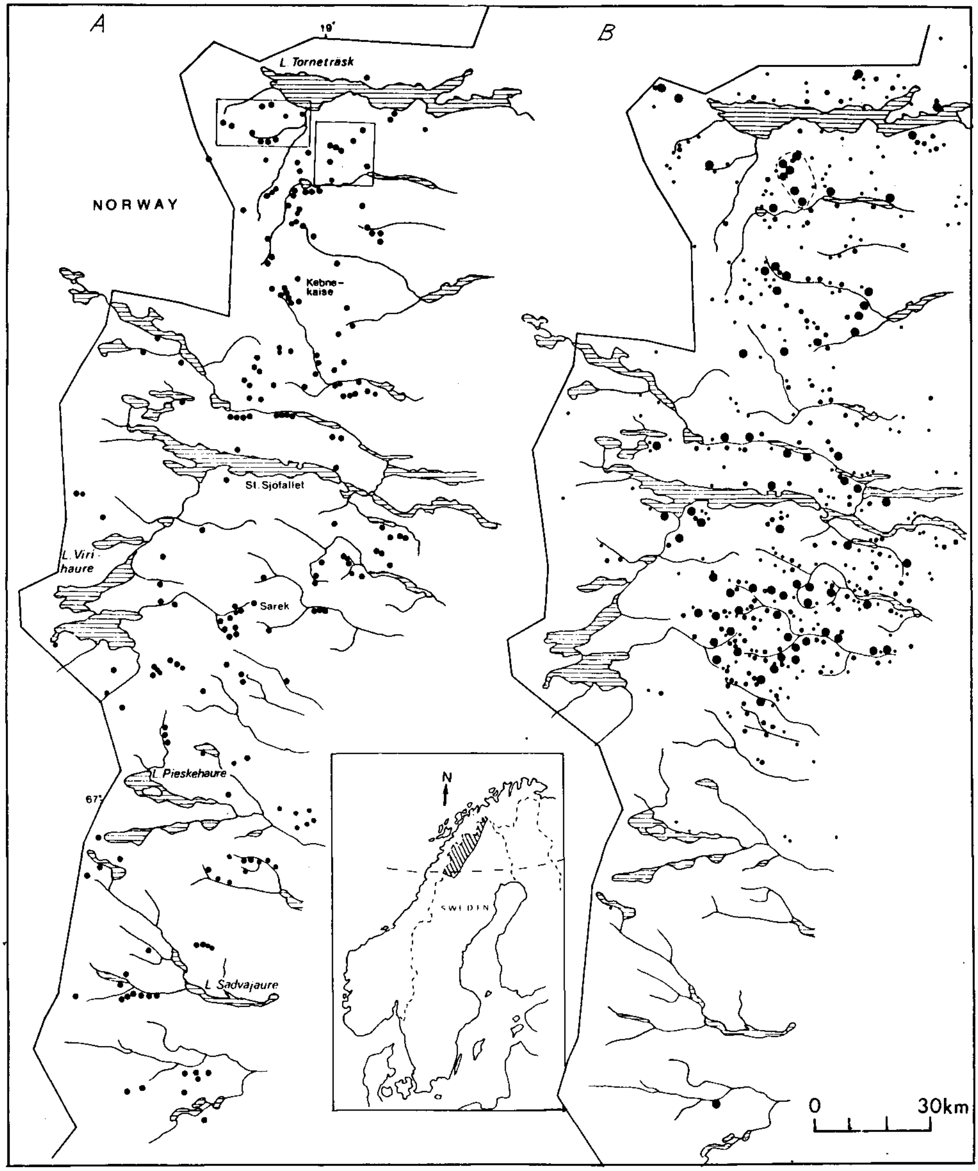

Fig.19.2. A. Slush avalanche sites. B. Debris flows. Inset: location map.
Right-hand map: small dots signify 1-2 cases, medium dots 3-5 cases, large dots >6 cases. Source: Geomorphological maps issued by *Statens Naturvårdsverk*. Both maps, slightly shortened, from Nyberg (1985).

consisting of snow of a different quality from the water-saturated snow. Slush avalanches move down the valley or slope often for several kilometres; they can occur on relatively gentle slopes in contrast to the steep slopes needed for other types of avalanche, and they belong to the late winter or even an advanced part of the snow-melt season.

The risk to people from snow avalanches is not great, but there have been some deaths. Avalanches are frequent along the Kiruna-Narvik railway (Rapp, 1961; Larsson, 1974; Nyberg, 1985). At the most dangerous part of the slope, the railway tunnel has now been lengthened, and warnings have been set up on the new road parallel with the railway. Danger from snow avalanches also affects the new Suorva-Ritjemjokk road along the mountain stretch of the Stora Lule Älv (Larsson, 1976); the most important are of the slush type.

The main reason why people are not often harmed by snow avalanches in Sweden is that no people live in the most dangerous regions, and the present tourists are crowded into the pistes of the southern, more gentle mountains. If off-piste and cross-country skiing were to become more popular, the situation might change. The dangerous slush avalanches normally occur between the winter and summer tourist seasons, and at a time when the migrating Laps have not yet arrived. I found traces of a big avalanche, probably of the slush type, in the 1960s in the Norra Storfjället area, crossing the Viterskal valley from a side valley. When I reported it to one of the hotel keepers in the main Ume valley not far away, it seemed to be unknown, but photos of a major avalanche in the same spot were later shown to me by the same man. The avalanche crosses a much-used tourist path. Events when people really were in danger are reported by Nyberg (1989).

Snow avalanches, like rock falls, are much more of a hazard in Norway, because of the higher and steeper relief, higher precipitation and, particularly, greater population along the lower-lying bases of avalanche-frequented slopes. Houses may be placed in protected sites, but the same is not always true for roads (Ramsli, 1951, 1981).

3. Processes and hazards in valleys containing thick clay and silt deposits

3.1. Clay slides

Clay slides are frequent in Sweden and include some really hazardous events. Slides with areas exceeding 1ha happen every second or third year (Cato and Engdahl, 1982) and major catastrophic slides (>10ha) about once a decade during the last 40 years (Viberg, 1982). Annual costs are estimated by Viberg to be at least 10 million Swedish Kr, while the direct and indirect annual costs to society during the last 30 years have amounted to 50-100 million Kr according to Cato and Engdahl. Loss of life has happened several times. Clay slides represent the most serious type of geomorphological hazard in Sweden.

The distribution of clay slides has been shown on small-scale maps by Wenner (1951), and more recently by Inganäs and Viberg (1979), the southern part of whose map is reproduced in Fig.19.3. There are few slides in the north, with the exception of a minor area around the mouth of the Ångermanälven. Figure 19.3 shows that the clay slides belong to river valleys and some coasts. With a few exceptions, the western and eastern slide areas are almost identical with those of steep-sided joint valleys in southern

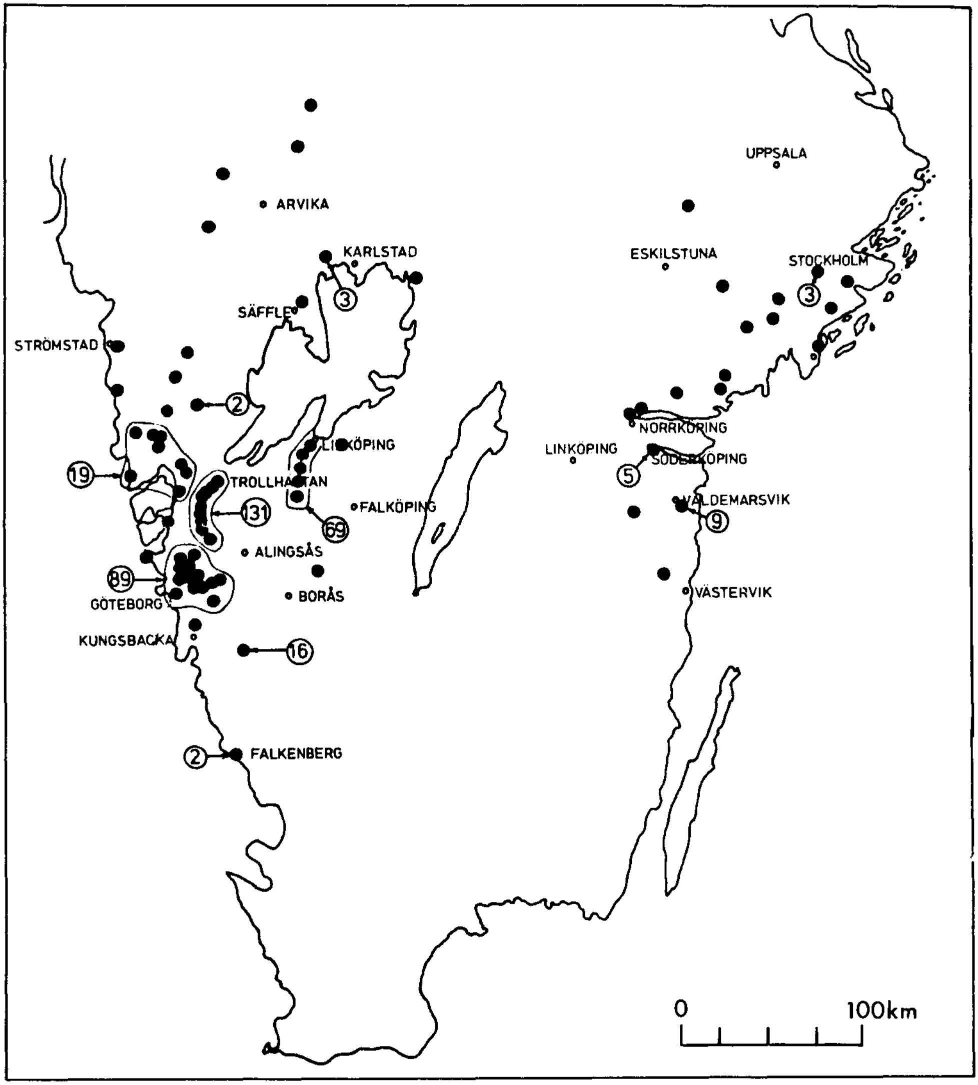

Fig.19.3. Clay slides in southern and central Sweden according to Inganäs and Viborg (1979). Numbers in circles indicate numbers of slides in those areas.

Sweden. The slides in the south-west are far more numerous, particularly those in the Göta Älv valley and its tributaries. There are also frequent slides in the surrounding areas, especially along the Lidan river towards Lake Vänern. There is a comprehensive literature about clay slides in south-west Sweden, in contrast to that available for other geomorphological hazards. The references given at the end of this Chapter are certainly not complete, particularly in the fields of geotechnical investigations and geological mapping.

The Göta Älv between Lake Vänern and Göteborg has rocky and often steep valley sides, and thick clay deposits in the valley floor. The tributary valleys have similar characteristics. Because of the greater post-glacial land uplift in the north, the Göta Älv is incised below terraces in its upper reaches; below the water surface, the main channel is always entrenched with steep sides, even where the surrounding land is flat (Sundborg and Norrman, 1963). The river has the greatest discharge of any in Sweden. It was canalised long ago and, in this century, regulated for hydro-electric power. The 24-hour regulation above the power plant at Lilla Edet and the longer-term regulation of the Vänern discharge (which means that the maximum discharge from this great lake is somewhat higher than the natural flow), are important factors: together with the permitted increase in size of boat using the channel, lateral erosion has been enhanced and bank slides more easily triggered (Sundborg and Norrman, 1963). On the other hand, bank slides have always occurred, including many too small to be included in slide statistics, and there have been similar slides in tributary valleys (e.g., Lind, 1975) and elsewhere. Such bank slides mean loss of farmland, but are not especially dangerous. They are controlled by bank protection works against lateral erosion.

Real hazards are presented by the larger-scale, far-reaching slides with numerous easily visible scars. For the Göta Älv valley, information is given by Frödin (1919), Sundborg and Norrman (1963), Järnefors (1959) (in a series of 3 maps, scale 1:20 000, of the Quaternary deposits), Viberg (1982) (with slide maps and information about quick clays and artesian water pressures), and Cato and Engdahl (1982). Most big slides are undated, but some are better known.

The slide with the largest area (37ha) at Bohus/Jordfallet occurred around 1150 (^{14}C dating of a log), but nothing else is known about it. The slide at Intagan in 1648, some 15km south of Vänern, is documented in contemporary records (Järnefors, 1957). From a terrace, a clay area of 25-30ha slid out into the river and dammed it for a while. The area belonged to Norway at that time, but people were killed on both sides of the frontier, altogether at least 85. This catastrophe is the greatest due to natural causes that has happened in Sweden.

Many other major slides are summarised by Sundborg and Norrman (1963), dating for example from 1733, 1750, 1759 and 1806. The latter two were of the "bottleneck type" in which the dry crust at the transition from terrace surface to river bank offered some resistance, and the wet clay masses flowed out through a narrow opening in the crust. Most major slide scars, dated or not, belong to the upper part of the valley and the tributary named Slumpån. The loss of farmland has been substantial, but nothing is known about loss of life, until the big slide events of recent decades.

The first of these occurred 15km north of Göteborg: this was the slide at Surte on 29 September 1950 (Fig.19.4), on a gently sloping (not really terraced) clay surface (Jakobson, 1952; Caldenius and Lundström, 1956). The total slide area was 20-25ha, occupied partly by houses for workers in the Surte glassworks a few hundred metres north of the slide. As it happened when the men had gone to the factory and children to

Fig.19.4. The Surte slide. Note the bulge into the river (lower) and the disturbed road and railway. The clay crust has been broken into separate narrow blocks, indicating the movement in the soft clay below (photo from Caldenius and Lundström, 1956).

school, few persons were at home and only one was killed. The houses moved up to 150m, some split into two or overturned, but as they were solidly built (as houses were at that time), people who stayed in the houses survived.

Only seven years after the Surte disaster, another great slide happened on 7 June 1957 at the Göta pulp factory, 40km farther upstream (Odenstad, 1958). The slide area was somewhat smaller than that in Surte, but more elongated, and stretched more than 1500m along the eastern river bank. Parts of the factory were damaged. A slowly opening clay fissure, curving towards the bank, gave warning to the boats at the quay. The latest episodes of the slide were characterised by rapid movement, as in Surte, the slide extending from the area between the fissure and the river bank, towards the valley side and northwards along the river. Only three of the 200 workers in the factory were killed.

The latest big slide occurred on 30 November 1977 at Tuve, at the side of a small tributary valley of the Göta Älv (Hillefors, 1977; Rudberg, 1978; Jansson and Stål, 1981; Larsson and Jansson, 1982). The slide was slightly larger than that at Surte. At Tuve, a modern suburb of Göteborg, built of detached, terraced and apartment houses, was partly destroyed. Sixty-five houses were destroyed, others damaged, and nine persons died, mainly housewives and small children. Most people fortunately had not returned from work or school. Some houses were moved more than 200m; in general they suffered greater damage than at Surte owing to modern, less solid construction.

There are no traces of older slides in the Tuve valley, but several in other tributary valleys, some the same size as in the Göta Älv valley (Caldenius, 1946; Hillefors, 1979; Cato and Engdahl, 1982). Some have been dated, and have involved loss of life. Big slides have also occurred outside the Göteborg area, for example the large landslide at Sköttorp by the Lidan river on 2 February 1946 (Odenstad, 1951). Here a long stretch of the river bank failed, including part of the field behind. In a list of slides, Wenner (1951) puts a question mark against 1 October 1918 at Getå, east of Norrköping. The biggest railway accident in Sweden happened here through failure of the railway embankment and derailment of a train, killing 40-45 people; was a clay slide involved in the slope failure here?

A correct interpretation was given long ago in an unsigned article (*Järnbanebladet*, January 1919, p.5-8). The railway ran along an old fault-line scarp, parallel with the shore of Bråviken Bay, with a road between. The embankment was founded on sand and silt underlain by clay. The weight of the embankment and the layers below it had increased through infiltration of heavy rains, causing sliding in the clay below. The slide caused an outward bending of the road, a rise of 1.25-2m in the shore line and a bulge out in the sea with an irregular surface as in Surte and Tuve. The situation is well shown in an early military air photo (Fig.19.5) taken the following day. It is significant that the movement started 5 minutes before the train arrived, judging from the disconnection of the railway telegraph line. All the facts are consistent with the Getå catastrophe being caused by a clay slide.

Further information can be gleaned from eye-witness accounts of the Surte, Göta and Tuve slides (e.g. Jakobson, 1952), together with immediate field visits by experts and air photo interpretation. The slides seem to have started from minor initial slides on

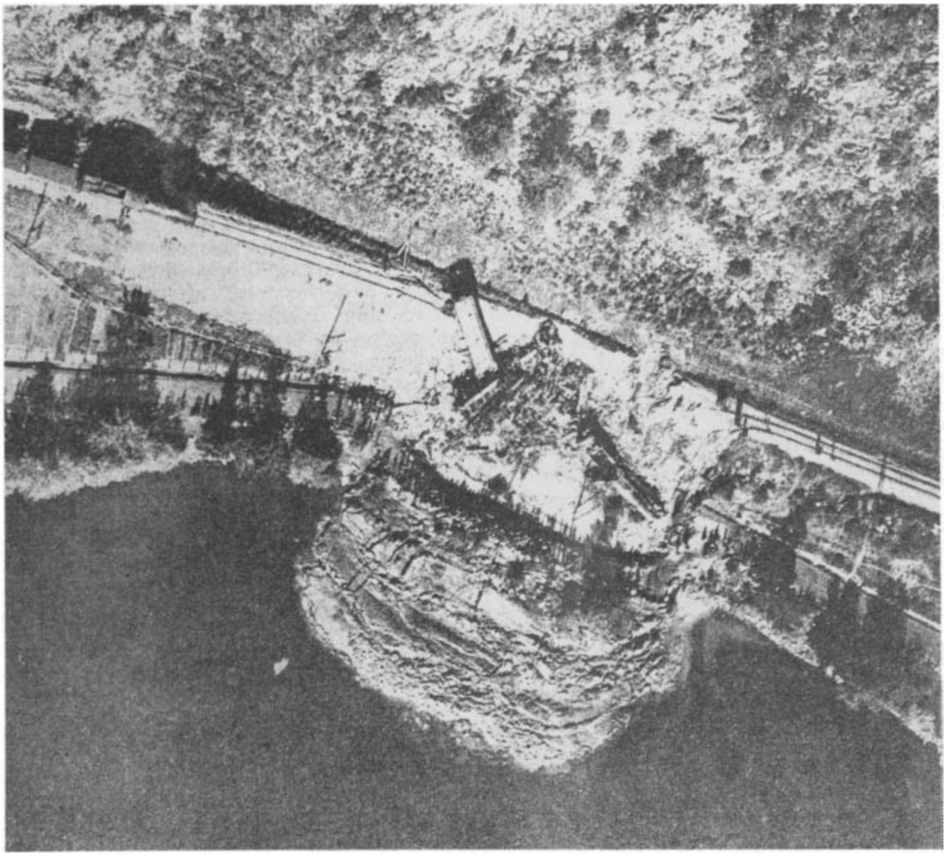

Fig.19.5. The railway accident at Getå, 1 October 1918. The air photo was taken one day later from a military plane at an altitude of 250m. A bulge similar to that at Surte has developed in Bråviken Bay (lower); the surface seems to have cracked, and the road distorted, also in a similar way (photo from *Järnbanebladet*, Jan. 5-8, 1919)

steeper parts of the slope at Surte and Tuve, or from a place close to the river bank at Göta. When the first slide moved down, the clay exposed in the steep back scar lost support, and a second slide was triggered, followed by a third, and so on. The slide thus expanded retrogressively, but at Surte and Tuve it was also progressive through increased weight on the lower clay surfaces by the sliding masses, sometimes overthrust (Caldenius and Lundström, 1956). The uppermost dry clay crust split into blocks, whose pattern to some extent shows the course of the movement (Fig.19.4). The upper parts of the slide areas sank, 5-8m at Surte and up to 10m at Tuve. The lower parts show raised bulges. At Surte and Göta the river was temporarily closed to traffic. The slides seem to have lasted only a few minutes; at Tuve, for instance, the duration was slightly less than 4 minutes according to cable failures in the initial and final slide faces. The ground surface was afterwards uneven owing to the blocks of dry crust tilted in different directions, but in the older slides (e.g. Utby, 1806), the surface has become fairly even, partly because of agricultural activity.

More information about geology and geophysical properties can be obtained from borings in the slide areas and their surroundings. These show that thin sand and silt layers often interrupt the clay sequence, and very often the clay is underlain by gravel, sand or silt layers lying directly on the bedrock. Clay samples from various depths have been tested for shear strength, sensitivity, safety factor, chemical parameters, electrical resistance and pore-water pressure. The presence of quick clay is very important. Quick clay is one in which there is a rapid change from the solid to the liquid state, for instance caused by movement. In a marine environment, the clay was originally laid down in a flocculated state owing to the presence of salts: it therefore has an open structure with large pore-spaces. The salts were supposed to strengthen this structure, but on exposure to air and fresh water following uplift above sea level, salt leaching starts and the strength was said to be progressively reduced. This simple theory is now being challenged; the properties of quick clay seem to be more complicated (Talme, 1968; Rosenqvist, 1977). Artificial injection of salt increases the stability of the clays.

The explanations have improved with time. A major role is often assigned to pore-water pressure (observed as artesian pressure in wells and boreholes), in the sand and silt layers also and especially at the basal sliding surface (e.g. at Tuve where the whole 20m thickness of clay has taken part in the movement; Larsson and Jansson, 1982). The importance of pore-water has led to several attempts to make correlations with precipitation. The slide frequency in the southern part of Sweden is higher in the autumn, according to Wenner (1951) and Viberg (1982); the latter also states that the frequency in northern Sweden is higher in the spring. The correlation is not too good, however: the Göta slide occurred in June, and in the case of the Surte slide, precipitation before the event was not particularly high.

The influence of man is considered to be important by Wenner and Viberg. Building of roads and railways, house construction and pile driving (e.g. at Surte) can cause ground shaking which can transform quick clays from the solid to the liquid state. Another point is that the apparent increase in the frequency of slides, and of severe slides this century, may be a product of better documentation (Viberg, 1982).

It can be seen from maps and field observations that some slides, at Intagan, Surte, Göta, Tuve, etc., occurred in broad concavities in the rock surface, a common form in these glacially sculptured areas. Concavities mean centripetal concentration of surface water and groundwater towards water-transporting layers within the clay. Pore-water pressures could then reach danger levels even if the months just before the slides were not particularly wet.

Finally, the reasons for the slides may not be the same in every case, and it is also probably sometimes a combination of different factors. Many scientific problems remain to be solved.

3.2. Gullying and lateral river erosion

Fluvial activity in Sweden started everywhere from scratch, following ice retreat or uplift of the surface above sea level. This first happened about 14 000 BP and is still going on. Since the commencement of fluvial activity, there has been no significant

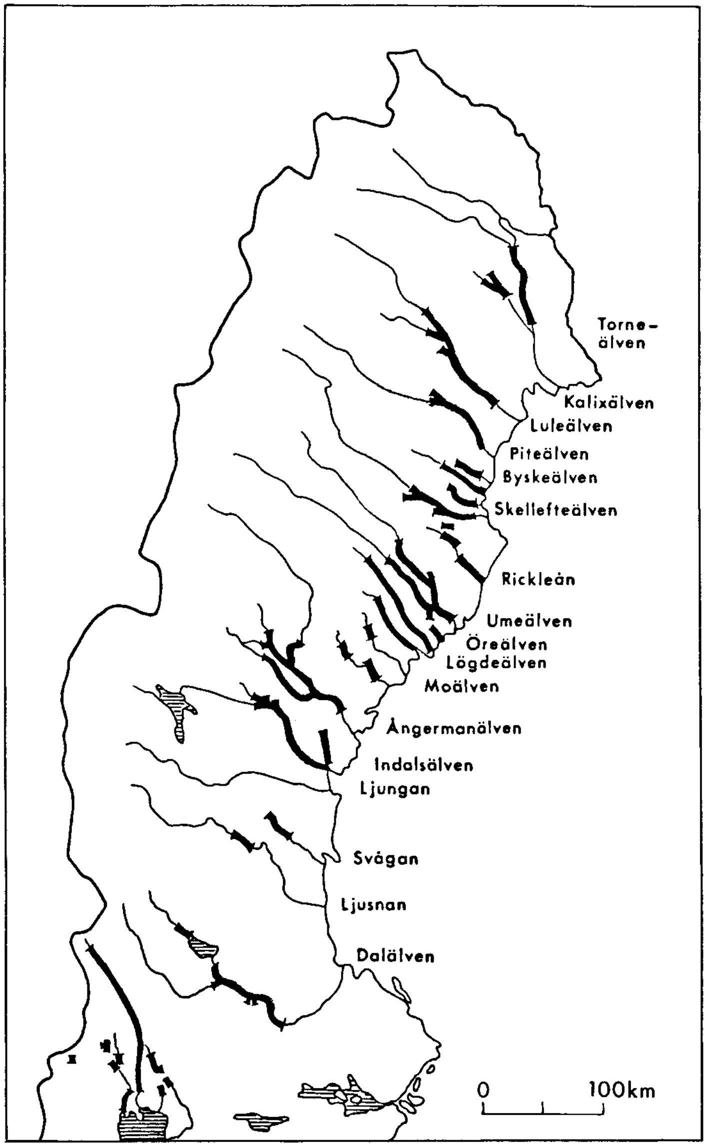

Fig.19.6.
Valley stretches in Sweden dissected by gullies, according to Bergqvist (1986)

erosion of bedrock, only a modest amount in till, but more in glacifluvial deposits and clay, and a great deal in silt and fine sand. This influence is shown by deep river incision, controlled by external or local base-levels, the latter provided by bedrock outcrops, till or occasionally coarse glacifluvium. As a result, all important rivers now show steps or basins in their long profiles; in addition, there are similar features possibly inherited from preglacial times. The present terraces were originally built as deltas, when the river mouths moved down-valley continuously or intermittently during uplift. The time available is less than 10 000 years in northern Sweden and the dominant impression is that the development has been rather fast. The difference in altitude between terraces and the present river is often 50m or more in Västerbotten, and up to 80m in the Öreälven valley (Rudberg, 1954), probably the highest figure in Sweden. The rapid river incision in silt and fine sand is complemented by zones of deep gullies along the river banks, often densely spaced and up to 1km or more in length. Some are dry, others utilised by small rivers coming from outside the gullies. A few cut through to the bedrock or till. Such a gully landscape (Fig.19.6) is typical for most northern Swedish valleys (Bergqvist, 1986), and in south and central Sweden where silts are present.

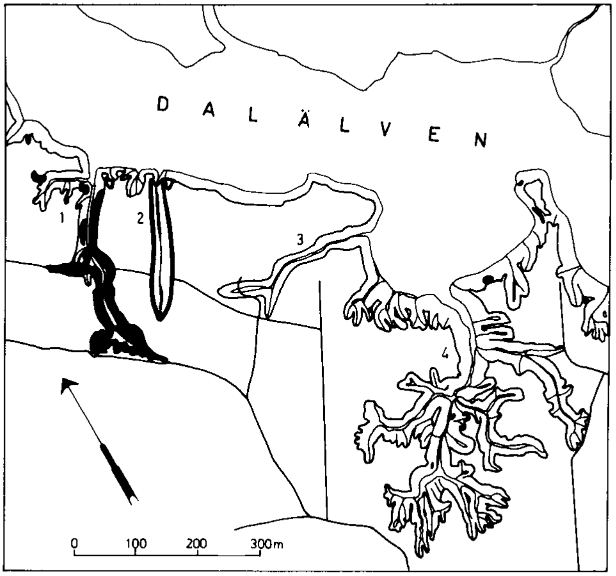

Fig.19.7. Gullies on the southern bank of the Dalälven. Redrawn from part of a map of 1913 (De Geer, 1914). Black signifies fresh erosion; the heavy black contour outlines a gully eroded during the last 100 years. According to Olivercrona (1937) valley number 3 was formed after 1813-16, and valley number 4 has grown. The formation of such gullies has been described as very fast in contemporary sources. Note the connection between small roads and gully tips.

River incision, and the associated gullying, must have been fast, especially in the earlier post-glacial stages of rapid uplift, but there were few people at this time to be affected.

When downcutting is arrested by local base-levels, lateral erosion can become severe. At present it damages farmland and property. Exact measurements are few, but for the meandering parts of the Klarälven, Sundborg (1956) found bank retreat of over 1m per year by comparing old surveys with modern air photos and field checks.

At present the gullies look mainly fossil and normally forested, but contemporary erosion has been noted in some places. A detailed map of the gullies on the south side of part of the Dalälven is shown in Fig.19.7 (De Geer, 1914; Bergqvist, 1986). Caldenius (1925) found that erosion (older or recent) was often related to man, with the construction of roads, ditches, etc. Olivercrona (1937) compared surveys from 1641-43, 1712, 1813-16 and De Geer's map of 1913, finding that some of the gullies already existed on the oldest map, but that some new ones, up to 500m long, had been formed since 1813. Many farms were forced to move during the continued, man-induced formation of new gullies. In the Öre Älv valley, the one with the highest terraces, Nordström (1984) observed a new gully growing by 15-20m in one day, and Ivarsson and Forsgren (1988) described another example. In both cases, human activity such as gravel quarrying or building of tractor roads played a clear role. Fredén and Furuholm (1978) give an instance where construction of an unpaved road for forestry in Värmland, on a steep slope in sand and silt, resulted in a gully 100m long and 20m deep in three days, when rain was added to snow-melt.

3.3. Draining of lakes

As in other formerly glaciated areas, Sweden has large numbers of lakes, some being rock basins, others dammed by superficial deposits (or a combination of both). Many lakes are connected with the fact that the rivers have not always found their last interglacial courses again. If dams of unconsolidated material are breached, either naturally or by man, rapid emptying of the lakes and temporarily high discharge can result.

The greatest and most famous event was the tapping of Lake Ragunda in 1796, described in detail by Ahlmann, Caldenius and Sandegren (1924). The lake was 24km long, partly rather narrow and shallow, being gradually filled with post-glacial alluvium. It was dammed by a ridge of glacial deposits, mainly sand, but before 1796 its outlet was over a rocky ledge, giving a high waterfall and narrow canyon downstream. This prevented local navigation, including timber floating. Plans had been worked out to improve this situation, and several attempts made to breach the damming ridge. Excavation by a foreign contractor suddenly proved too successful, and in the evening of 6 June, the river, at a high water level, abruptly broke through. The lake emptied in a few hours, the flood wave causing damage to fishing installations, saw-mills, etc., all the way down-valley for 90 - 100km to the delta in the Gulf of Bothnia. When the lake had been emptied, river incision and headward erosion in the soft lake sediments unprotected by vegetation began. The drop in water level was 35-40m. Headward erosion slowed down now and then as more resistant material was encountered, but the first 8km of retreat is said to have occurred during the first night of the catastrophe (though Ahlmann suggested this was an exaggeration). Retreat continued until a rock threshold was reached at the present Hammarforsen waterfall, 17m below the original water level. Headward erosion above Hammarforsen is not recorded in detail, but resulted in the formation of new terraces in glacifluvium in the Ammerån valley, the largest tributary to the former Ragunda lake (Ahlmann, 1924, pl.4). Gullying in the lake floor immediately followed on the headward erosion. Slope retreat and terrace formation continued for a few years. In the delta area, new islands were created and shorelines altered (Ahlmann, 1924; Arnborg, 1967). The Indalsälven delta is more developed than others in northern Sweden, partly owing to the Ragunda lake catastrophe. No people seem to have been killed on the day of the lake tapping, but some perished during subsequent days of erosion and bank sliding in the lake area. To mark the bicentenary of the event, a volume with contributions from many scientists has recently been published (*Döda Fallet och Ragundasjön*, 1990). It gives an account of the long history of planning by the local people, as well as by the King himself, for the improvement of communications. After the catastrophe, the matter occupied the Law Courts for 200 years!

Other cases of lake tapping have been described from Lakes Arpojaure in northernmost Sweden (Ahlmann, 1914; Caldenius, 1922) and Örträsk, northern Västerbotten (G.Lundqvist, 1927). These and other lake tappings have been summarised by G.Lundqvist (1944), all caused by man's attempts to improve nature (improvement of timber floating, local dams for power production, etc.). Lake drainage has been very fast, sometimes in a few hours. The catastrophic floods released sometimes caused emptying of the lower lakes in a system and further erosion.

A few dam failures have been described after 1944 (*Dammsäkerhet*, 1987), the most outstanding being the collapse of the modern Noppikoski dam on the Oreälven. It happened on 7 September 1985, following extremely heavy rain. Few deaths have resulted from tapping of natural or man-made lakes, but damage to forest and property has been serious.

4. River floods

Floods are less important in Sweden than in many other countries, but can occur during unfavourable combinations of events, as when the usual high-water stages owing to snow-melt are augmented by rain, or when there is continued heavy rain in late summer or autumn so that lakes are full and the ground saturated. Floods occur locally in most rivers, but to a lesser extent in northern Sweden (except for parts of the Torne älv and Kalix älv), because of recent flow regulation. Their impact is lessened by the siting of settlements on terraces or valley sides. Out of sixty-six listed serious flood

events, most are found in central or southern Sweden, often on small rivers in the plains (*Dammsäkerhet*, 1987, appendix 1)(Fig.19.8). Factors to explain the distribution include:
1. the occurrence of low-lying settlement in vulnerable positions;

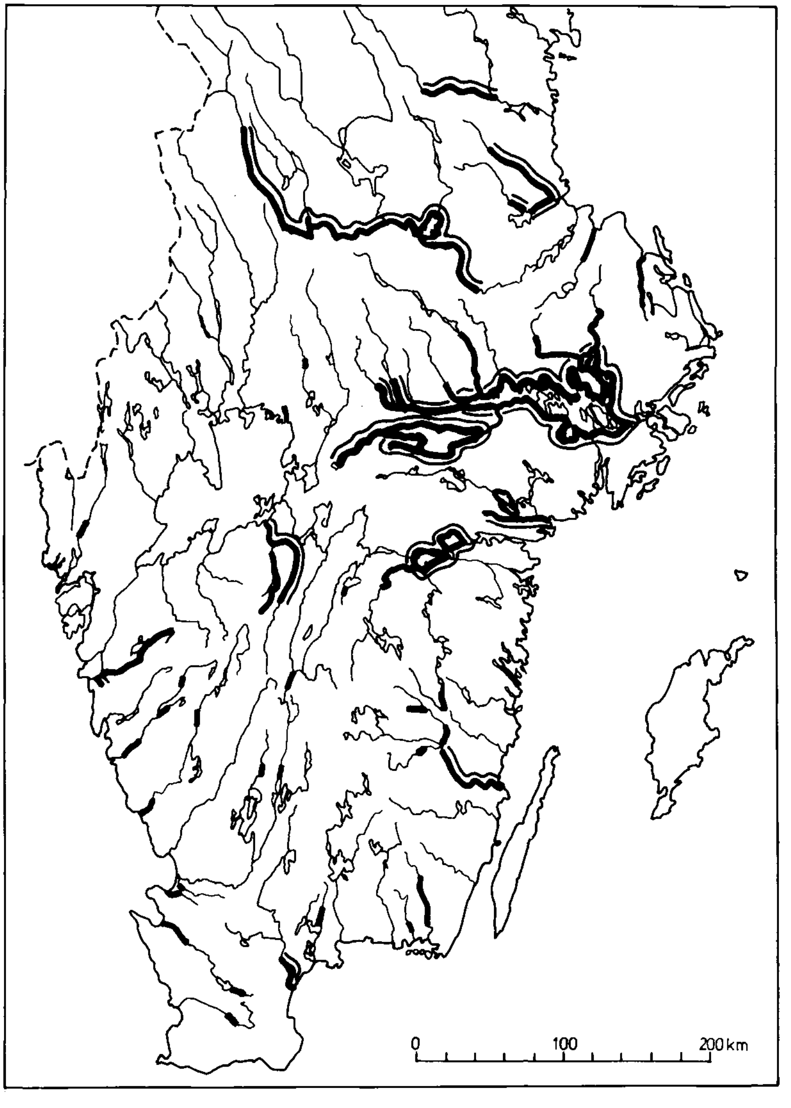

Fig.19.8. Valleys affected by river flooding. Made after a list by SMHI and published in *Dammsäkerhet* (1987). Valleys marked with double lines have experienced the greatest damage. In some years, floods also affect other valleys.

2. relatively few lakes in the drainage basin;
3. significant snow cover in the basin most winters.

Floods in Sweden have only occasionally caused loss of life, but the costs of damage repair may be quite high, 400 million Kr for the decade 1977-86; in the bad year of 1985 and only for the province of Gävleborg, the cost of damage was 100 million Kr (*Dammsäkerhet*, 1987). Protection works that have been undertaken include better lake regulation, widening of narrow river sections, protective dykes and improved flood forecasting.

A few areas on the west coast experience flooding during storm surges.

5. Soil and wind erosion; snow drifting

Neither are very significant in Sweden, but there have been some cases of rapid erosion in areas of sandy-silty soils of glacial origin. Soil erosion by running water occurs locally in many parts of Sweden in spring on unprotected fields; the cause is mainly concentrated rainfall.

Many papers about wind erosion in southern Sweden have been published, notably for Skåne and adjacent provinces, including the island of Gotland (e.g.Åhman, 1974; Mattsson *et al.*, 1983; Mattsson, 1984). This type of erosion is most typical of the spring when the soil is dry and new crop growth has not yet covered the ground. It is concentrated in restricted areas, such as to the south of Kristianstad, around Lake Våmbsjön, and near the south-east coast. Sugar-beet fields are particularly at risk (Nihlén, 1984). The risk seems to be increasing because of the change from dairy farming to grain, and the trend towards larger unprotected fields. The annual costs of soil erosion, particularly by wind, are by no means negligible.

Otherwise, wind action seldom gives rise to hazards in Sweden, mainly because of the protective vegetation. Exceptions are few, such as the south-western coastal margins where glacial and post-glacial deposits have encouraged dune formation since about 1500, sometimes invading cultivated land in the past but now mostly controlled (Norrman *et al.*, 1974).

Snow drifting by wind is important in some winters on open fields in Skåne and also in some other parts of south and central Sweden. In some winters, lines of communication can be interrupted. In the mountains, wind activity can be quite strong, resulting in snow redistribution and in erosion of bare patches on vegetated surfaces. These patches often look fresh (Rudberg, 1968) and podsol horizons may be exposed (Rudberg, 1984). One naturally thinks of over-grazing as the cause, but this is not recorded from present-day Sweden. As the tundra has been only very locally used for cattle and sheep, it must be a matter of herds of semi-domesticated reindeer, whose numbers fluctuate but showed peaks in 1910, 1931, 1955 (*Rennäringens ekonomi*, 1983) and 1989 (291 800 animals - *Statistik Årsbok*, 1990, tab.74). The damage to the tundra and soil degradation is no real hazard in itself, but may initiate other potentially hazardous processes on steep slopes.

6. Shoreline processes and hazards

Present-day shore processes do not produce any great hazards. In south-east Skåne where uplift is zero or there is actual subsidence, cliff erosion of glacial deposits has caused some loss of farmland and tourist cottages (Lindh, 1976). On the western shore of Gotland, marl and limestone cliffs are retreating at 0.4-1.25 cm/year (Rudberg, 1967b; re-calculated using other assumptions as 2-4 cm/year - Rudberg, 1984). There are a few rockfalls resulting in loss of forest or grassland but hardly any houses. At the southern end of Lake Vättern where there is transgresssion because of greater uplift and an outlet in the north, a large glacifluvial deposit is being cliffed, with retreat of 40-50 cm/year (Norrman, 1964), inhibiting suburban development of Jönköping and Huskvarna. An old church has already been destroyed by such lake-shore erosion.

7. The impact of recent social and land-use changes on hazards

Social and economic changes have gathered pace in the last half-century, and are altering the level of risk from natural processes. The population is increasing and moving to the cities, particularly to the conurbations of Stockholm, Göteborg and Malmö. Many small and medium farms are disappearing, and farming is becoming more and more concentrated in the most favourable areas of the south. Field sizes are increasing, often by removal of trees which formerly provided shelter. Cattle grazing on natural pasture has almost ceased; and cattle no longer graze in the forests.

Timber cutting practices have radically changed in recent years. Heavy machinery now tends to replace manpower and the amount of clear-cutting has increased dramatically. The impact is greatest in areas (high altitude, high latitude) where forest regeneration is slow (100-150 years at least). Official data (*Skogsdata*) show that, in the four northern provinces and northern Dalarna, the total clear-cut area (including areas with seedlings less than 10 years old which, from a distance, look like clear-cut areas) is about 20 per cent. Individual clear-cut areas may be more than 10km long (e.g. in northern Jämtland: Andersson, 1980); around the upper reaches of the river Ljungan, the forest has been removed in broad bands amounting to 50 per cent of the area (Rafstedt, 1987). For replanting, the ground is ploughed to depths of several decimetres, and for the safety of the tractor driver, the furrows run in the slope direction, not along the contours. Clear-cutting usually stops about 100m below the timber line. The timber line is traversed by ski pistes which are numerous and often closely spaced in the southern mountains.

The greatest changes are seen in the rivers. Most are regulated and changed to stairways of lakes, partly artificial, usually widened, and occasionally including quite new lakes. The regulation is in connection with hydro-electric power production, and the water levels in some lakes may rise or fall by 20m or more. There are now 140 dams more than 15m high, and three are higher than 100m (at Trängslet on the Österdalälven (Fig. 19.9), at Seitevare and Messaure on the Luleälven: *Dammsäkerhet*, 1987). The higher

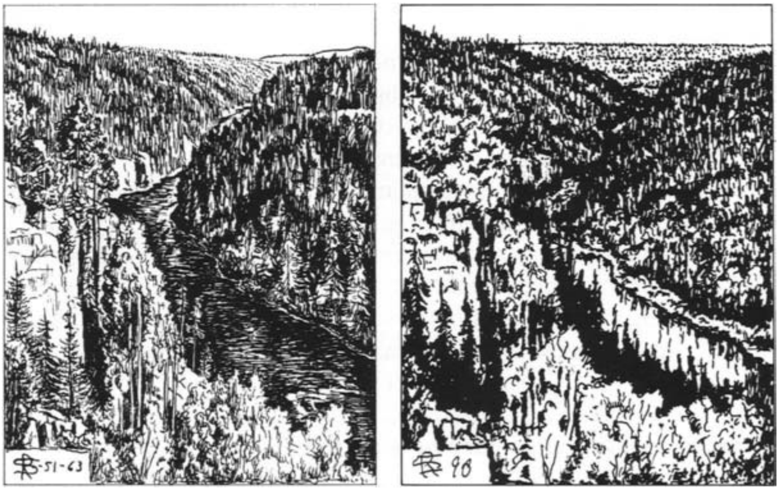

Fig.19.9. Part of the Trängslet valley, Österdalälven, before and after construction of the dam 125m high; behind the dam is a reservoir about 70km long. The right-hand sketch has been drawn from a colour slide taken by Jan Swantesson.

dams are usually earth dams. Of the 12 main rivers in northern Sweden, only three and a branch of a fourth remain in their natural state, though minor rivers remain unchanged.

The question must then be asked, what impact will such man-made changes have on the course and pattern of geomorphological hazards? With regard to rapid processes on steep slopes, such as rock falls, avalanches and debris flows, there is no reason to expect changes in incidence, but there may be some risk of more accidents with an increase in cross-country skiing and tourism in early summer.

There are three types of hazard where an increase in risk may be predicted, and these are also most probably the major hazards for the future. The first two are already well known, but the consequences of the third are much more difficult to foresee.

7.1. Clay slides

Clay slides in south-west Sweden will continue to occur. Salt leaching is going on slowly, together with lateral river erosion and undercutting of the river banks. In the problem areas, population and economic development have continued to grow. A major clay slide in one of the more densely populated parts of the Göteborg area could be a serious risk for the future. The risks are well known by the local authorities, and much work has been done including geotechnical investigations, protection against bank erosion, reduction of critical slope angles, and evacuation of some dangerously situated houses. The total cost so far is 30 million Kr for the Göteborg city area.

7.2. Dam failure

There are about 10 000 dams in Sweden, most of them low and with small lakes, several of them built for timber floating in the past. They are often in poor condition but not regarded as a great risk (*Dammsäkerhet*, 1987). The main concern is certainly the high dams and large reservoirs. Rapid breaching of one of these dams would be a disaster for the valley below, many times greater in magnitude than the tapping of Lake Ragunda. Collapse of a dam higher up in a river valley would cause problems for the lower ones and for population living in the lower parts of the valley even if the dam in question is situated in an unpopulated area. The failure of the Noppikoski dam in 1985, as mentioned above, triggered new work on dam safety; in this case, however, the dam and the lake were not large. More serious has been the threat of failure of the Messaure dam. When the water level was raised for the first time to its maximum height in July 1963, two irregular depressions developed close to the crest, 1.5 and 1.3m deep respectively. The water level was lowered by 3m and investigation showed that the depressions were caused by arching lower down in the dam core, probably caused by fault-related movements in the bedrock surface owing to pressure of overburden during construction (Nilsson *et al.*, 1964).

Another threat of failure occurred in one of the three Suorva dams on 4 October 1983, where a leak was observed releasing 8000 l/minute of sediment-laden water. It was later found that part of the dam core was eroded, probably owing to insufficient sealing of joints in the bedrock (*Dammsäkerhet*, 1987). The repairs were successful in both cases. Other minor accidents have also been reported. Recommendations from a State committee include better preparatory work, better organisation and, not least, better forecasts of exceptional precipitation. As precipitation records are too short (this century mainly), mathematical models need to be developed for events with longer recurrence intervals (Brandt *et al.*, 1988).

7.3. Deforestation by clear cutting

Clear cutting on the present scale in high altitudes and high latitudes has never been undertaken before; experience of the effects of deforestation has so far been mainly limited to timber felling in the south. In this situation we have more questions than answers.

The first question is how long the clear-cut areas will remain without protective forest. Forest in high latitudes or altitudes has often proved difficult to rejuvenate, even if all surfaces are planted with new seedlings. There is a scarcity of good indigenous seed, and foreign seed (such as the Canadian Pinus contorta) has not proved successful in difficult areas. A warning is given by the broad areas at around 700m without coniferous forest around the old mining town of Röros in Norway, where the forest was cut for fuel in the smelting works.

Other problems may be linked to local or meso-climatic change. The temperature range will most probably increase on clear-cut areas and wind speeds will be higher, causing snow drifting and uneven snow cover, but snow melt will in general be faster. At the same time there will be hydrological changes. Trees lose 350-550mm annually by evaporation and transpiration; if they are removed, this amount is transferred to the groundwater. The water table rises and this in turn results in an increase of runoff from the clear-cut areas (Grip, 1982; Grip and Rodhe, 1985). The annual increase for ten experimental plots amounted to 90-400mm, averaging about 200mm (Grip and Lundin, 1987). How much a river basin is affected, and how much shorter the response time between precipitation and runoff will be is still hard to say. Tentatively, some river floods have recently been attributed to clear cutting, but most of the scientific papers such as Brandt *et al.*(1988) claim that this is not correct and that clear cutting has a low influence on a whole river basin. In our case, when slopes are of interest, any local increase of runoff is of central importance.

An important question particularly relevant for this paper is the danger of rapid and catastrophic erosion on clear-cut areas, and most of these, even those at high altitude, tend to be ploughed with furrows and ridges lying open to rain for several years. Investigations of ski pistes in the southernmost mountains of Sweden (Giessübel, 1988) showed local increases of erosion. I myself briefly checked, in the autumn of 1989, some 20-30 ski pistes in the mountains a little farther north, most of them less than 30 years old, and found that not quite half of them were slightly damaged, notably by new rills, deepening of artificial drainage trenches, or lateral widening of ditches when erosion had met solid rock. The behaviour of thin till covers may be noted in this respect, as till thicknesses in the mountains are often quite low.

The idea of ploughing the clear-cut areas is to give better chances for the seedlings to reach mineral nutrients, but these same nutrients may be lost through leaching and erosion on unprotected bare ground, though loss of soil minerals may be difficult to observe directly. The bottom of the furrows never slopes evenly, usually consisting of depressions and humps (often boulders). No detailed work seems to have been done about the effects of ploughing. Increased runoff and erosion on clear-cut slopes was, however, shown in a pilot study by Larsson and Gretner (1982) on the valley sides of the Klarälven. The slopes here are steeper than average in Sweden and do not seem to have been ploughed, but are crossed by several tractor roads for timber transport. Sand and silt are dominant in the area but till also occurs. Gullies associated with the tractor roads are sometimes several metres deep and landslides have occurred in till, owing to slope undercutting or super-saturation above a temporary frost table. The landscape changed greatly after clear cutting, and it may be predicted that minor hazards for the people living in the valley are not far away. In the case of clear-cut areas on steep slopes, including ski pistes, the main danger is likely to be from exceptional rains.

8. The impact of climatic change

So far, any attempted predictions of future hazards have been made on the basis of the present-day climate. In the near future, however, significant changes of climate are expected in view of the greenhouse effect and ozone-layer depletion. Various scenarios of global warming have been put forward, with maximum warming of 6°C (or even over 10°C) in the latitude of Sweden (Brouwer and Falkenmark, 1989; Thompson, 1989). Precipitation is also expected to be higher around such latitudes, and for central Sweden to be greater than the expected rise in evapo-transpiration. To some extent, the expected increase in the dust veil will mitigate the rise in temperature, but by how much is difficult to estimate (Thompson, 1989). Climatic change based on these scenarios will increase the risk for two of the main hazards in Sweden: clay slides and dam disasters. In respect of the third main hazard, the changes should promote better forest growth at high altitudes and in high latitudes, but with increasing precipitation there will perhaps be some greater risk from debris slides on steeper slopes, particularly those that have been ploughed or harrowed. A warming of climate might also be preceded by increased frequencies of extreme weather events (Thompson, 1989; Brouwer and Falkenmark, 1989), and Swedish hazards are in some cases related to just such events.

10. Conclusion

This review has shown that clay slides are the most important hazard in Sweden, and this situation is unlikely to change in future, despite all precautions, as will also be the case with major dam failures. Lesser hazards have been exemplified in various fields. To view these in their correct perspective, one needs to compare them with other types of (non-geomorphological) hazard. The pure costs of just one minor geomorphological disaster, for example, could be compared with the costs of extra domestic heating during a cold winter - which is of the order of 2000 million Kr.

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FORMER YUGOSLAVIA

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Editor's note: This Chapter was written before the tragic events in this area. The use of the term "Yugoslavia" in the title has been retained, however, as it would make no sense to try to divide the Chapter into several parts.

1. Introduction

Although the first geographical meeting on natural disasters organised by Yugoslavian geographers dates only from 1983 (*Naravne nesreče v Yugoslaviji*: see Radinja, 1983), scientific work on hazards was already active in the last century. In the field of seismic hazards, the disastrous Ljubljana earthquake of 1895 prompted the establishment of the country's first seismic recording station in 1897. Today there are fourteen such seismic stations, and institutes of seismology have been set up in each of the capital cities, together with an international seismological centre in Skopje. It was after the Skopje earthquake of 1963 that the then federal government acted to pass into law legislation concerning the safe construction of buildings and other structures in areas of earthquake risk.

The study of flood hazards has been mainly carried out by geographers and hydrologists. In Serbia, Gavrilović (1981) has published a review of floods during this century. The periodical *Geografski zbornik* published in Ljubljana by the Geographical Institute AM ZRC SAZU has in the last two decades contained twenty articles on the geography of floods and their impact in Slovenia. Landslides and rockfalls are mainly being investigated by geologists in terms of their mechanism and origin, but geographers have also studied their effects on human activity. Bognar (1983) and Lazarević (1983) have discussed types of landslide, while Gams (1989) has examined the terminology of mass movements.

In the same year (1983) as the first Yugoslav meeting on natural disasters, Slovenian geographers organised a similar meeting (Gams, 1983) on natural hazards in Slovenia, which stimulated further reviews of such phenomena, including publication of a journal entitled *Ujma*, which reports on all kinds of natural and man-made disasters in Slovenia.

This is published by the Slovenian headquarters for civil protection; its six annual volumes so far contain 1000 pages detailing these disasters. Another significant conference was held in Budva in 1986, when Yugoslav experts involved in natural disaster mitigation and civil protection met to discuss problems raised by major natural catastrophes, leading to the publication in Belgrade of the volume on *Elementarne nepogode i katastrofe* (1987). The Proceedings of a meeting in 1992 report on floods in Slovenia (Orožen-Adamič, 1992).

Organisation of civil protection from natural hazards is linked to military defence. Most effort has concentrated on what can be done to ameliorate the situation immediately after a disaster. Every employee in the communes, republics and the state pays a contribution deducted from his earnings to a fund for disaster mitigation. If losses exceed a certain fixed percentage of the Gross Domestic Product, the local administration receives support from higher-level authorities. Federal funds have so far mainly been used for reconstruction, community care and financial losses after earthquakes, floods, storms and droughts. In the areas worst affected by an earthquake, it is now possible to ensure that, within 10 years, the economy will have been restored and even improved (Gams, 1980).

2. Seismic hazards

The former territory of Yugoslavia, whose geological structure was primarily determined by the Alpine orogenesis, belongs to the Mediterranean seismic region. Out of a total area of approximately 256 000km^2, 1.4 per cent is potentially at risk from earthquakes with an epicentral intensity greater than IX (Modified Mercalli scale), 4.4 per cent between VIII and IX, and 20.8 per cent between VII and VIII: thus, over one quarter of the country is under threat of earthquakes with intensity greater than VI (*Veliki geografski atlas*, 1987). In the five-year period 1980-85, there were no less than 1022 earthquakes with epicentral intensities between III and VI, and nineteen exceeded VII.

Seismically, there are two zones of greatest activity in former Yugoslavia: (1) along the Adriatic coast and (2), Macedonia.

The Adriatic coastal zone corresponds to the subduction zone of the Italo-Adriatic plate plunging under the rising Dinarides. The most disastrous earthquakes here are in southern Dalmatia, Montenegro and Albania. In 1667, a violent earthquake destroyed Dubrovnik, with an estimated death toll of 4000-5000 persons (A on Fig.20.1; Sikošek, 1987). Also along this zone, there have been disastrous earthquakes in the Mt Biokovo (1763m) region, causing serious damage to the town of Makarska in 1886 and in 1962 (when the epicentral intensity was IX); in 1979, the earthquake in Montenegro claimed 105 victims, and destroyed or severely damaged 14 000 buildings (B on Fig.20.1). In the north-western coastal area earthquakes caused serious damage to the town of Zadar (C) in 1280, to Rijeka (D) in 1750, and to Idrija on the Idrija Fault in 1551; while the well-known Friuli earthquake (E) of 1976 occurred along the same fault. All along this

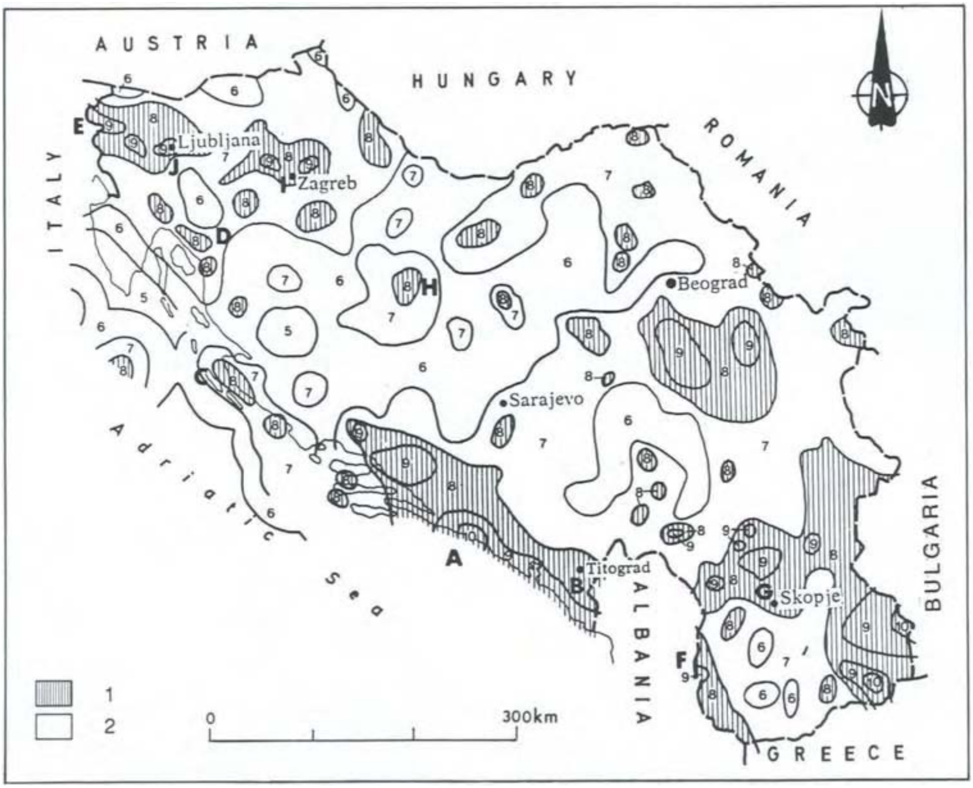

Fig.20.1. Seismic activity in Yugoslavia. The map shows the risk of earthquakes of different severity, based on records of past activity. The figures refer to epicentral intensities on the MSK scale, expressed in arabic numerals for clarity (e.g. 7 = VII). Areas characterised by earthquake intensities greater than VIII are shaded.

coastal zone, the old houses in villages are built of stone blocks and mortar, a form of construction highly vulnerable to seismic shocks.

In the Macedonia-Prokletije zone, disastrous earthquakes struck Debar (F) in 1968 (M = 6.4) and Skopje (G) in 1963 (epicentral intensity IX) when about 1000 people were killed.

Apart from these two high-risk earthquake zones, other major areas of earthquakes with intensities greater than VIII or IX are around the Kopaonik range (2018m), Zagreb and Ljubljana.

Detailed seismo-tectonic research (see *Elementarne nepogode i katastrofe*, 1987) has shown that many earthquakes, including those mentioned above, are associated with the contact zones between regions of crustal uplift or subsidence. This relationship is quite clear in the case of earthquakes along the Lim graben (e.g. the Debar seism) and the Vardar graben (e.g. Skopje). The disasters in Montenegro and Banja Luka (H; 1969 earthquake) were also related to such contact zones. The map of present vertical movements in Yugoslavia (*Recentna vertikalna pomeranja zemljine kore*, 1986) shows similar relationships in the Zagreb seismic area, where Mt Slijeme (1036m) is rising and the nearby Save trench is subsiding (e.g. the earthquakes in 1880 (I)). The same is true of the Ljubljana area (e.g. 1895 earthquake at D) where the Ljubljana Moor has been sinking for the last 500 000 years and basin sediments 170m thick have accumulated. Many Yugoslavian towns in the mountainous districts are situated in subsiding basins flanked by rising mountains. This concentration of population and associated economic activity in tectonically mobile areas heightens the seismic hazard. In Slovenia, for instance, the area potentially at risk from earthquakes of intensity IX or more amounts to 4.2 per cent of the area of the republic, but in it, 7.6 per cent of the population is concentrated (Radinja, 1983; Ribarič, 1984).

3. The flood hazard

Along the principal rivers of former Yugoslavia, 40 000km of main dykes together with 5650km of subsidiary dykes have been constructed. They protect about 20 000km^2 of land. These figures give some idea of the importance of flood protection in former Yugoslavia. About 90 per cent of the area potentially at risk from flooding is situated in the Danube basin (Fig.20.2). The degree of protection afforded from floods of different water levels is not exactly known. It is also impossible precisely to estimate the efficiency of the various flood control works - dykes, flood-relief channels, the few flood-retention basins and so on.

Figures 20.3 and 20.4 show the areas liable to flooding in Serbia and north-west Yugoslavia respectively. In terms of individual river basins, the Save basin contains about 4800km^2 at risk of flooding; the Drave 2500km^2 and the Danube (Dunav) 500km^2 (*Veliki geografski atlas*, 1987). The worst flood in this century in Serbia was in 1965, when the Vojvodina in Serbia proper and parts of Kosovo were inundated, totalling 4500km^2, together with 400km^2 in Baranja. In this catastrophe, 16 000 buildings were damaged or destroyed, as well as 214km of roads. A special problem encountered on the Danube is the formation of ice jams in winter or early spring (Gavrilovič, 1981). Research on the floods of the Velika Morava and the Save between Zagreb and Novska (Fig.20.4) and flood-control measures have been partly funded by international organisations. In 1989, a disastrous flood hit the valley of Krapina north-west of Zagreb.

In the mountainous areas of former Yugoslavia that comprise four-fifths of the state, floods threaten the lowest alluvial terraces in the large valleys and basins where the density of population is greatest. In 1962, floods in the basins of Macedonia (Skopje, Polog, Pelagonia and Strumica) inundated 650km^2; in 1979, 530km^2. Such valleys and basins in former Yugoslavia contain the best soil for cultivation in the mountainous districts. In the Titograd basin, the raised water level of Lake Skadar (Skutari) has at times threatened 145km^2 of land. Some poljes in the Dinaric karst are liable to flooding of much greater duration than along the normal rivers, in some cases lasting up to half a year (for example, Lake Cerknica: Kranjc, 1986). In the Imotsko-Bekijsko polje alone, the potential area of flooding amounts to 95km^2. The Cetinje polje in Montenegro is usually regarded as a dry polje, but after many dry years, a flood in 1987 caused severe damage to part of the town of Cetinje, its museums and factories.

Floods in the catchments draining to the Adriatic Sea are more modest in extent and tend to be isolated phenomena; some recent examples are on the Mirna river in Istra, the Ćepić polje, the Vrana polje (31km^2) and the marshy end of the Neretva valley.

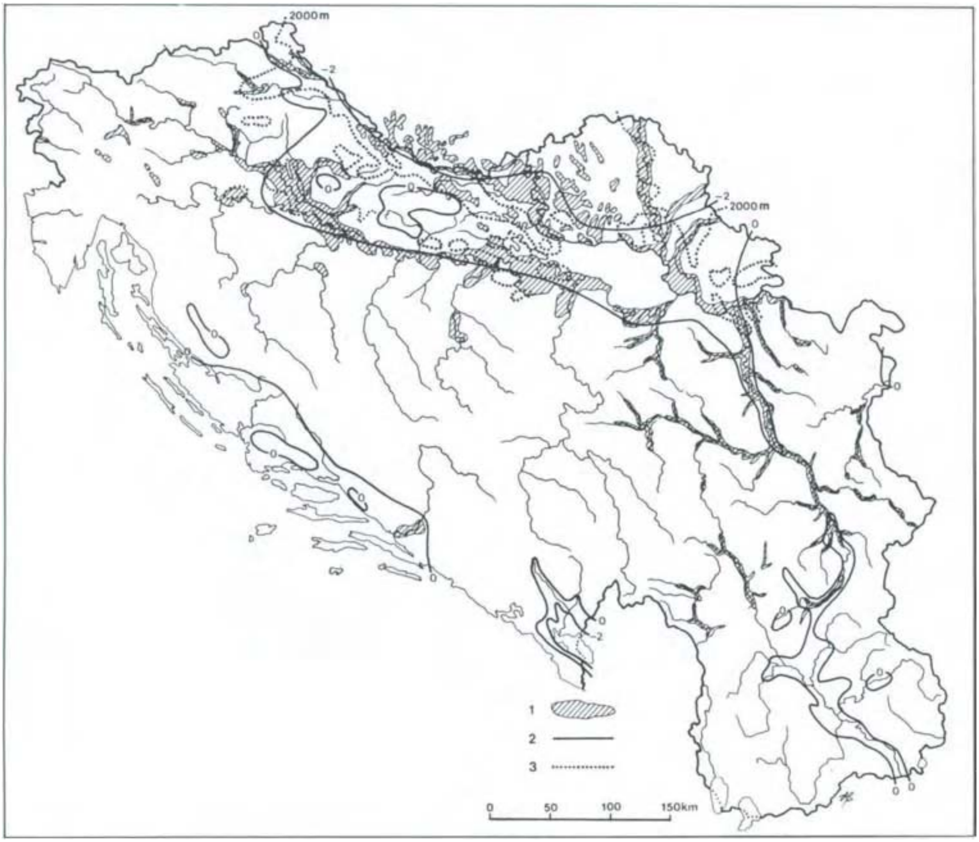

Fig.20.2. The main areas at risk from flooding in Yugoslavia, and their relationships with zones of recent tectonic subsidence. 1 - Areas of potential flooding; 2 - Isolines of recent tectonic subsidence based on repeated geodetic levelling (mm/year); 3 - Isolines at -2000m depth, marking basins of Tertiary and Quaternary sediments

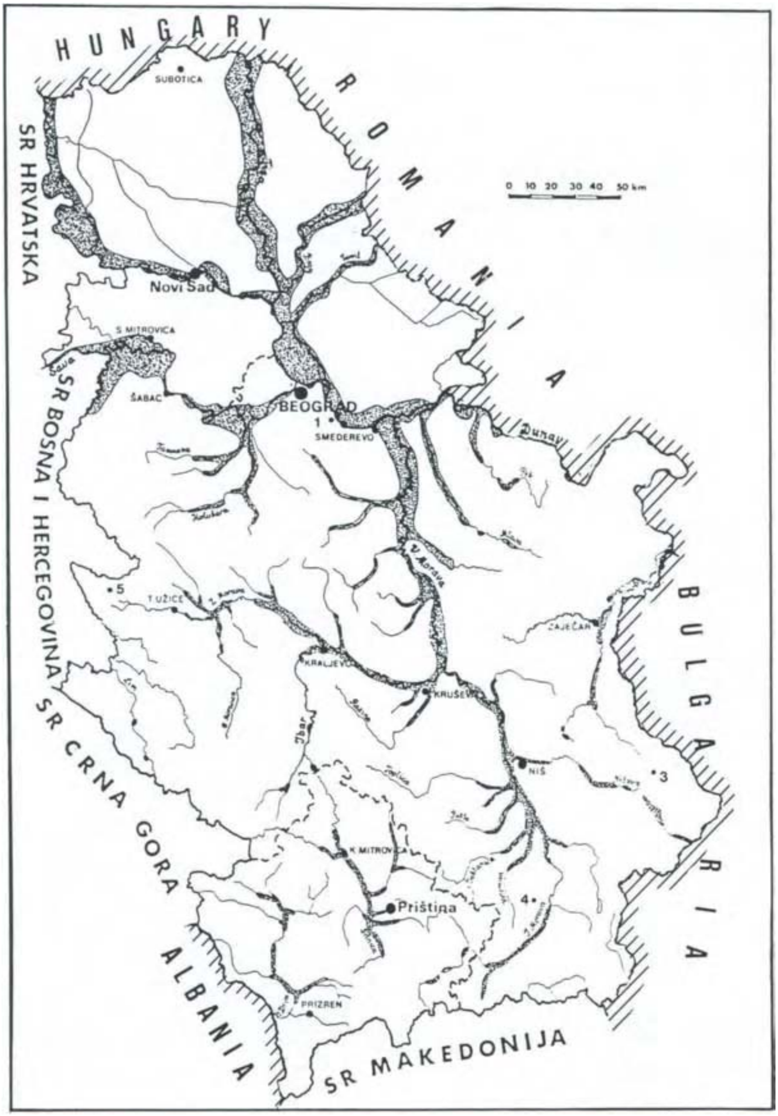

Fig.20.3. Areas of potential flooding in Serbia (Gavrilović, 1981)

The most extensive areas of flooding in the Danube catchment are located in the tectonic grabens, as in the case of the Great Morava, Drave and Save trenches, where there is active subsidence (*Recentna vertikalna pomeranja zemljine kore*, 1986). This relationship is also true in the case of the largest intramontane basins (for instance

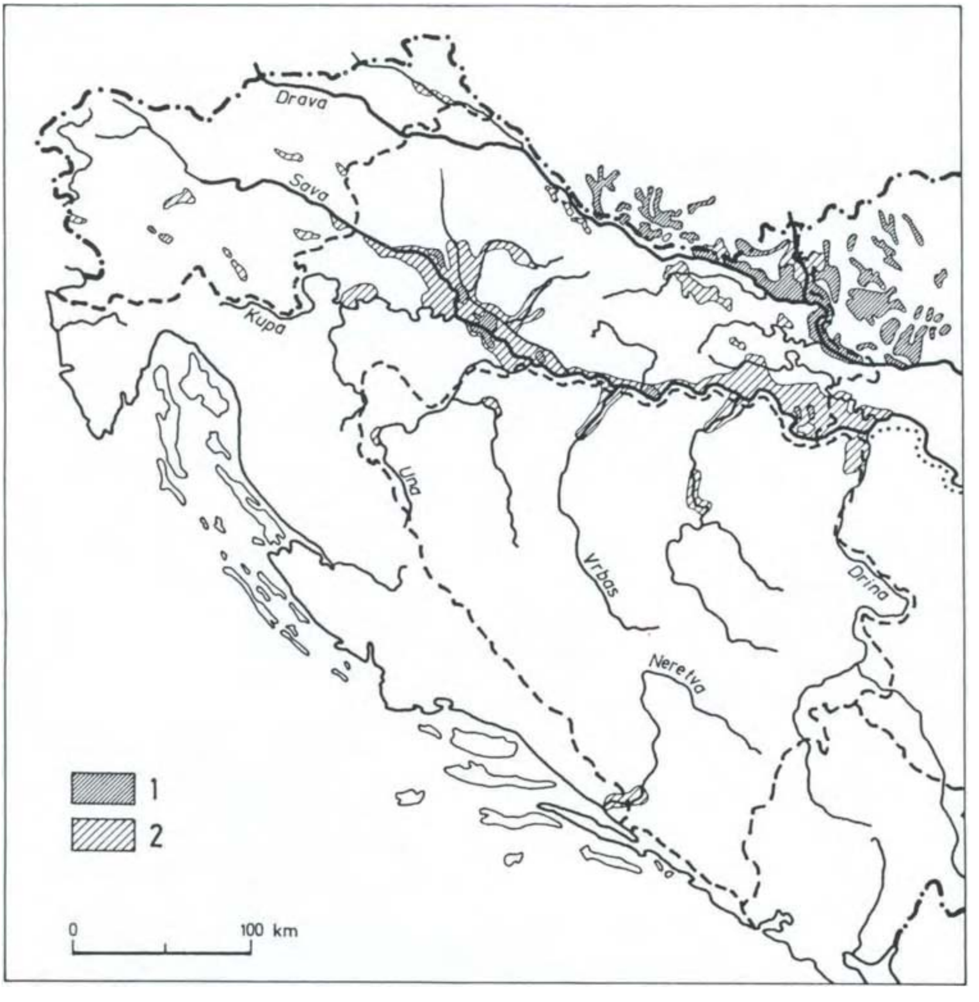

Fig.20.4. Areas of potential flooding in north-west Yugoslavia (Bognar and Gams, first draft). 1 - Areas of expected annual flooding; 2 - maximum extent of potentially disastrous inundation

Macedonia, Karlovac basin, Ljubljansko Barje, etc.). Floods in such basins have threatened the towns of Skopje (1962), Zagreb (1964), Karlovac (1989, 1992), Sisak and Osijek.

Coastal flooding in Yugoslavia is relatively unimportant, affecting only small areas along the Adriatic, mostly the artificially protected low-lying coasts near the main coastal towns in Slovenia and Dalmatia, and in a few cases, the islands.

4. Mass movements and soil erosion

The incidence of mass movements in Yugoslavia is strongly linked to relief and lithology.

4.1. Quaternary loess areas

In the eastern part of the Pannonian basin (in Vojvodina, Srem and Baranja), the edges of the loess plateaus are often steep and more than 10m in height. The instability of these slopes is increased by basal undercutting by the Danube and Drave rivers, leading to a variety of slope failures, especially slides and collapses (Bognar et al., 1981). The slip planes are often provided by intercalated layers of clay, silt or palaeosols. On the surface of the plateaus and more gentle loess slopes, piping has caused the development of surface collapses similar to karstic dolines and pits.

4.2. Tertiary sediments

The geological formations most susceptible to landslides are the Tertiary sediments (Fig. 20.5). Along the sub-Pannonian margin, these comprise molasse; along the Adriatic margin, flysch prevails. Both consist of alternating clays, marls, silts, sands and thin calcareous strata and are unconsolidated. The predominant surface forms are hills with a relative relief up to about 200m. They have steeper slopes on the western margin of the Pannonian basin. Here, precipitation increases to an average of 1200mm, and the maximum daily rainfall can exceed 100mm. After heavy rainfall, the soil layers and weathered sediments readily move in shallow but quite short (tens of metres) slides. Such superficial slides are very frequent: after storms their density can reach $1/km^2$ (Natek, 1989). Sometimes, larger slides develop, the largest (1 on Fig.20.3) on the right bank of the Danube between Beograd and Smederevo, named Rujište, being 4km wide, 700-800m in length and up to 50m deep.

4.3. Mountain areas and intramontane basins

In the mountainous area, the less stable slopes consist of schists, sandstones, metamorphic rocks, ophiolite and Quaternary clastic sediments (Bognar, 1987). The slopes least susceptible to landsliding are limestones (in the Dinaric karst plateaus) and the massive igneous rocks. In the basins and valleys, there are some long slopes built out of Tertiary sediments where large landslides have developed.

In Macedonia, such slopes have been strongly affected also by deforestation in the past to create pasture land. In recent decades, many pastures have been abandoned, but the dry summer climate of this area is not favourable to forest regeneration, and severe soil erosion has set in. According to Lazarević (1981), the total quantity of silt deposited and transported by rivers in Yugoslavia amounts to $350m^3/km^2/year$. Of this, 21 per cent is transported towards the Aegean Sea by the Vardar river draining south-east

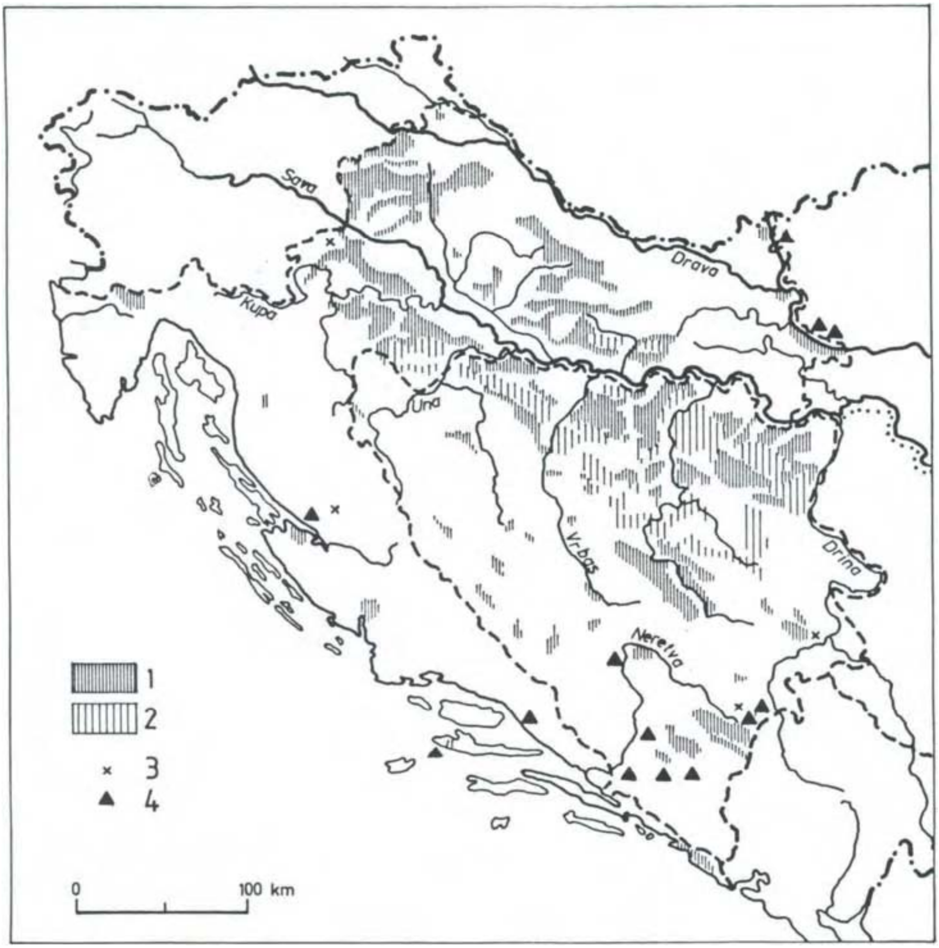

Fig.20.5. Susceptibility to landsliding in Croatia, Bosnia and Herzegovina. 1 - High to very high risk of landsliding; 2 - low to moderate risk; 3 - Slopes susceptible to rock slides; 4 - Major rock falls and debris flows (A.Bognar)

Yugoslavia, although this drainage basin only occupies nine per cent of the whole country.

Serious soil erosion is also a hazard in southern Serbia where both torrents and landslides in the foothills threaten roads and railways, especially in the Morava and Timok valleys. Outside this region, landslides present a risk to roads and railways in parts of the Drina, Bosna, Una, upper Save and Soča (Isonzo) valleys. Some gorges incised into the limestone or other massive rocks are threatened by rockfalls and slides.

4.4. Major landslide and rockfall events

Relatively little is known about the older disastrous landslides. In recent decades, the largest landslide was in the Visočica valley in the Stara Planina of eastern Serbia (3 on Fig.20.3). The volume of the slide is estimated at 1.5 million m^3. With a height of 35m, it dammed the river to form a lake with 35 million m^3 of water. The village of Zavoj was submerged and 1300 inhabitants had to be evacuated. Later, a drainage tunnel was constructed to empty the lake. In 1990, another tunnel to the Nišava valley at Pirot was built as part of a hydro-electric scheme and the lake re-formed as a reservoir for it. Near Vladičin Han (4 on Fig.20.3) in southern Serbia, a slide on 18-19 February 1977 buried the village of Jovac, destroying 40 farmsteads and damaging 170 others. The slide was 3km long, 500m wide and up to 50m thick: the volume is estimated at 150 million m^3. The Jovačka reka was diverted and a lake formed. The following year, 1978, saw another major landslide in western Serbia, at Mt Tara near the village of Rastište (5 on Fig.20.3). This measured 1km in length, 200-300m in width and contained 20 million t of debris.

In 1956, a landslide named Gradot in the basin of the river Luda Mara in Macedonia killed 11 shepherds and many sheep. Among the older landslides that have been recorded, that of 1857 on Mt Bovan in Montenegro is mentioned in the literature.

Rockfalls in the Julian Alps of Slovenia (Fig.20.6) have occurred at Jesenice (15 million m^3), at Studor in Bohinj, and on Kuntra hill, north-west of Kobarid in the Soča valley (*Ujma*, 1989). In 1989, a large rockfall in the Pasica gorge near Cerkno destroyed a museum-hospital of the second world war.

Rockfalls are mostly a phenomenon of the high mountains (Slovenian Alps, Prokletije mountains, etc.), and on the steep sides of gorges and the edges of limestone plateaus, especially where the latter are in contact with less resistant sediments beneath. On the flatter karst areas, there are small but numerous surface collapses owing to underground solution. Mining has caused some larger-scale subsidence in the areas of Tertiary sediments, for example, above underground salt mines in the Tuzla basin (Bosnia), where some settlements have been abandoned, and in the Velenje basin with its three lakes, one of which is 48m deep.

In the Adriatic coastal zone, rockfalls are particularly associated with overfolding which has emplaced Mesozoic limestone on top of (mostly) younger sandstones, shales and Eocene flysch. The higher slopes of Mts Trnovski gozd, Nanos, Notranjski Snežnik, Kozjak, Mosor, Biokovo and Rumija are covered with screes and ancient rockfalls. Landslides on the overloaded sediments of the foothills also occur. The calamitous 1979 earthquake in Montenegro triggered many slope failures, rockfalls and landslides (Gams, 1979). The Friuli earthquake of 1976, with its epicentre just 20km from the Slovenian border in the Soča valley destroyed or damaged some 12 000 buildings (Orožen-Adamič, 1979), but no rockfalls were recorded. Rockfalls were known to have occurred, however, in the nearby Karawanken mountains on the Austrian border during the earthquake of 1348, the year in which the town of Villach, thirteen villages, three castles and nine churches in Austria were destroyed (*Ujma*, 2, p.56) (see also Chapter 1, Austria, sections 4.1 and 9).

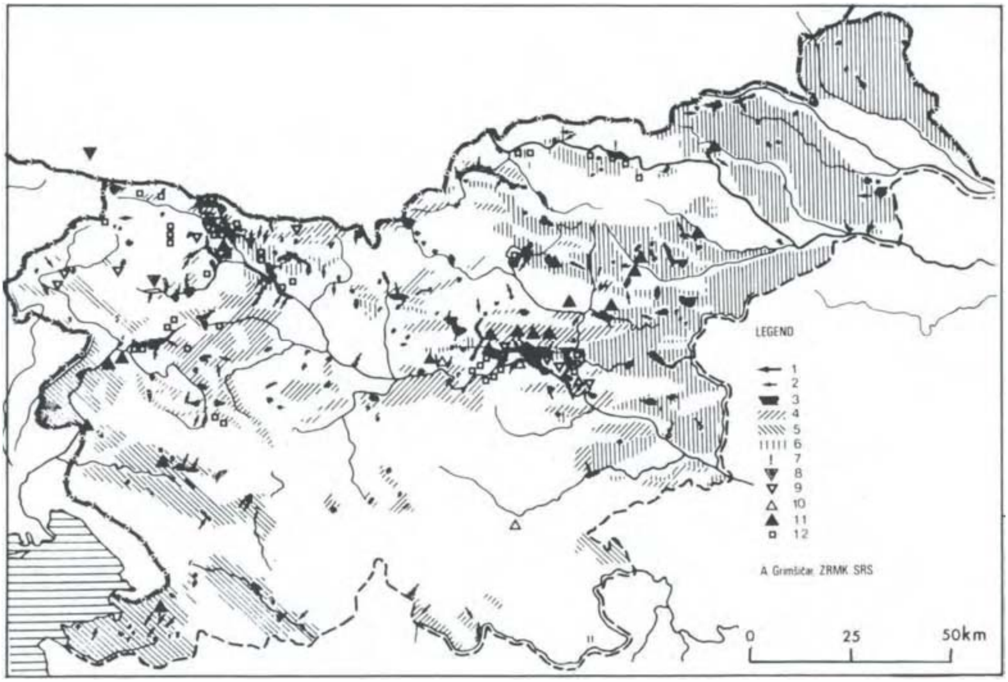

Fig.20.6. Lithology and landslides in Slovenia (after A.Grimšičar, 1983). 1 - catastrophic landslides; 2 - large landslides; 3 - slopes susceptible to landsliding; 4 - areas of schist; 5 - Eocene flysch; 6 - Tertiary undifferentiated; 7 - potential disastrous landslides; 8 - disastrous rockfalls; 9 - rockfalls; 10 - rock slides; 11 - man-made landslides; 12 - smaller rock failures

5. Avalanches

Behind the foothills and lower ranges of the Adriatic coastal zone rise the higher mountain ranges such as the Velebit Planina (2064m) and the Dinara Planina (1914m) where the heavy precipitation in winter falls mostly as snow. The same is true of the Slovenian Alps and the high ranges of south-eastern former Yugoslavia and the Albanian border. Avalanches have caused damage on the Stara mountains (2764m), in western Macedonia and the Prokletije mountains. In the decade 1973-83, in south-eastern former Yugoslavia, 48 victims were recorded, mostly in buildings buried by avalanches and on roads (Šegula, 1986). In the Slovenian Alps which attain over 2800m, numerous avalanches occurred in the winters of 1950-51 and 1951-52 (Gams, 1955)(Fig.20.7). In February 1952, avalanches in the Soča valley killed 15 people and destroyed 129 buildings (*Ujma* 1987, p.50). More than ten mountain refuges in the

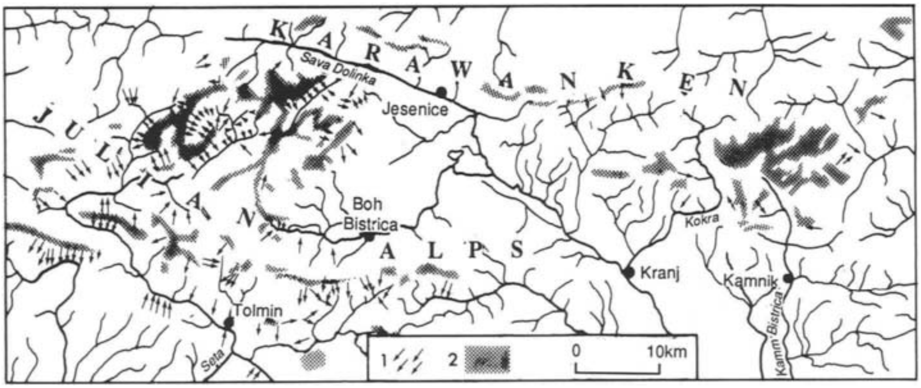

Fig.20.7. Avalanches in Slovenia in the winters of 1950-54 (Gams, 1955). 1 - Recorded avalanches; 2 - Rocky slopes highly susceptible to avalanches

Slovenian Alps are known to have been destroyed in the past. In Slovenia, the long-term record for the period 1877-1986 shows 465 deaths from avalanches, with another 187 presumed killed. Most of the victims were Austro-Hungarian soldiers on the front-line during the first world war in the Soča valley on 24 and 25 December 1915, and 8 March 1916 (Šegula, 1986).

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General Index

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Index of Place Names

Except for settlements of any size (cities, towns, villages) and self explanatory names (e.g. Baltic Sea), all entries include a reference to feature type, such as river, island, administrative area, and so on. The description is given in italics and usually abbreviated as follows:

a any administrative subdivision of a country (county, province, district, and so on)
i island(s)
l lake
m mount, mountain(s), mountain range, massif
r river
v valley