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.

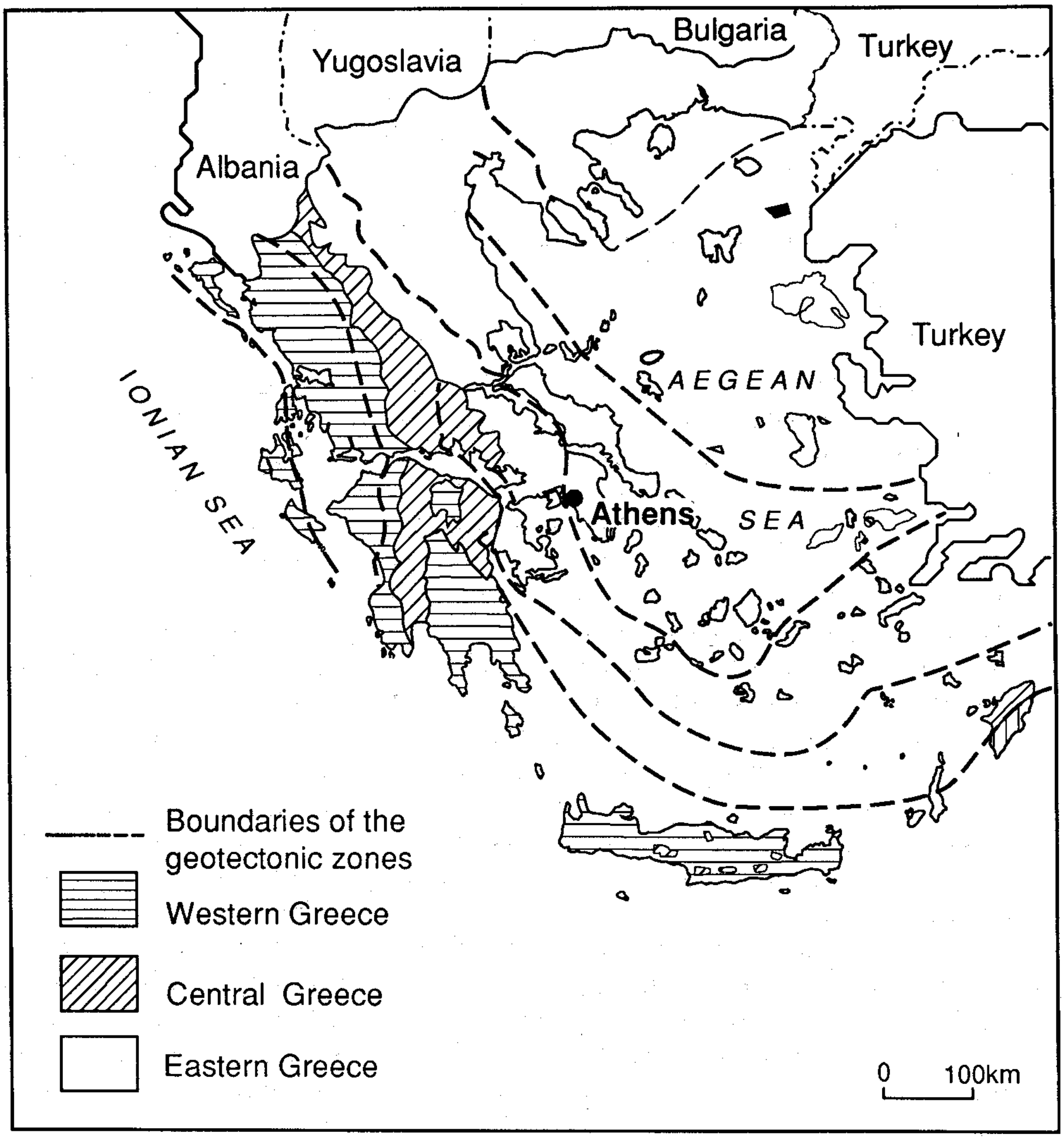


Fig.9.1. Geotectonic zones of Greece (Koukis, 1982)

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.

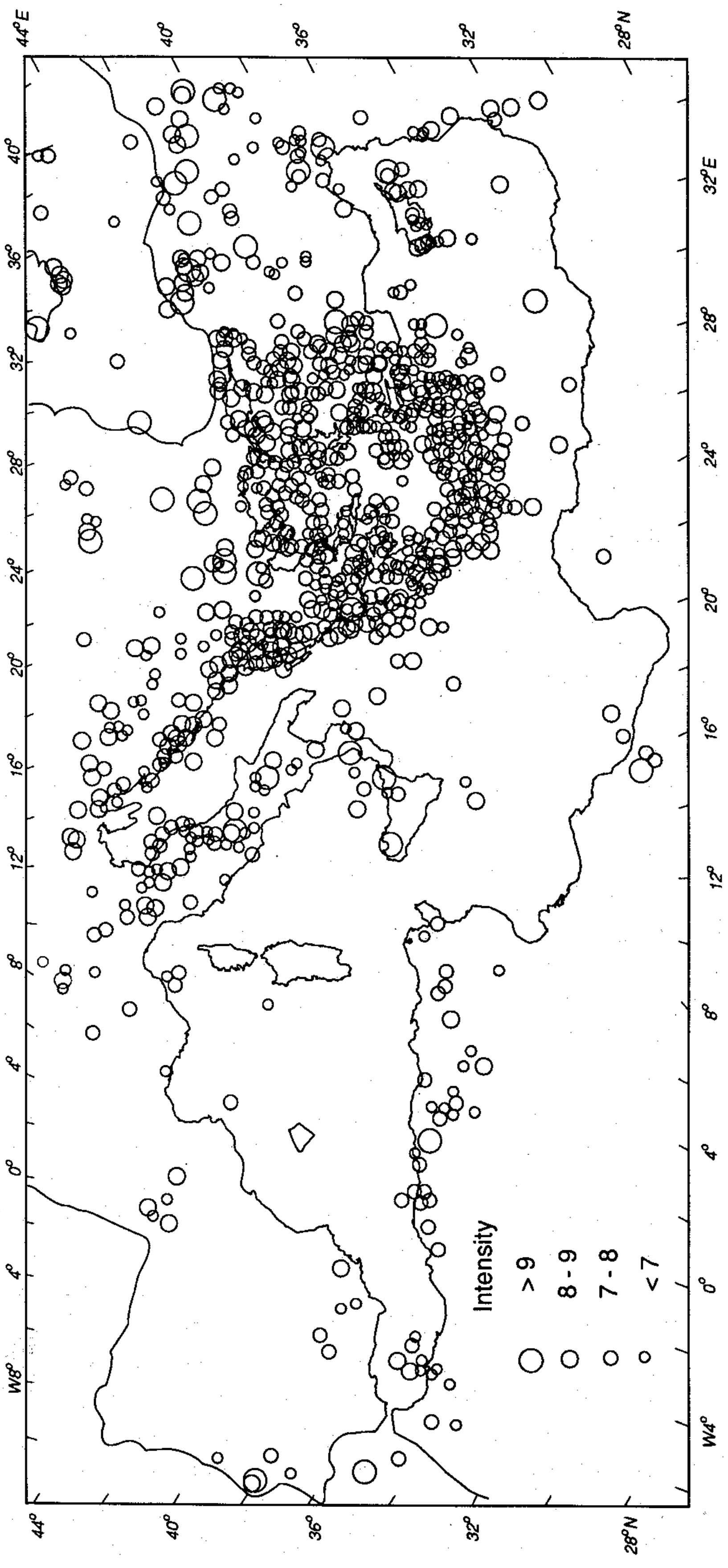
2. Seismic activity

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


44°E
40°
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Intensity
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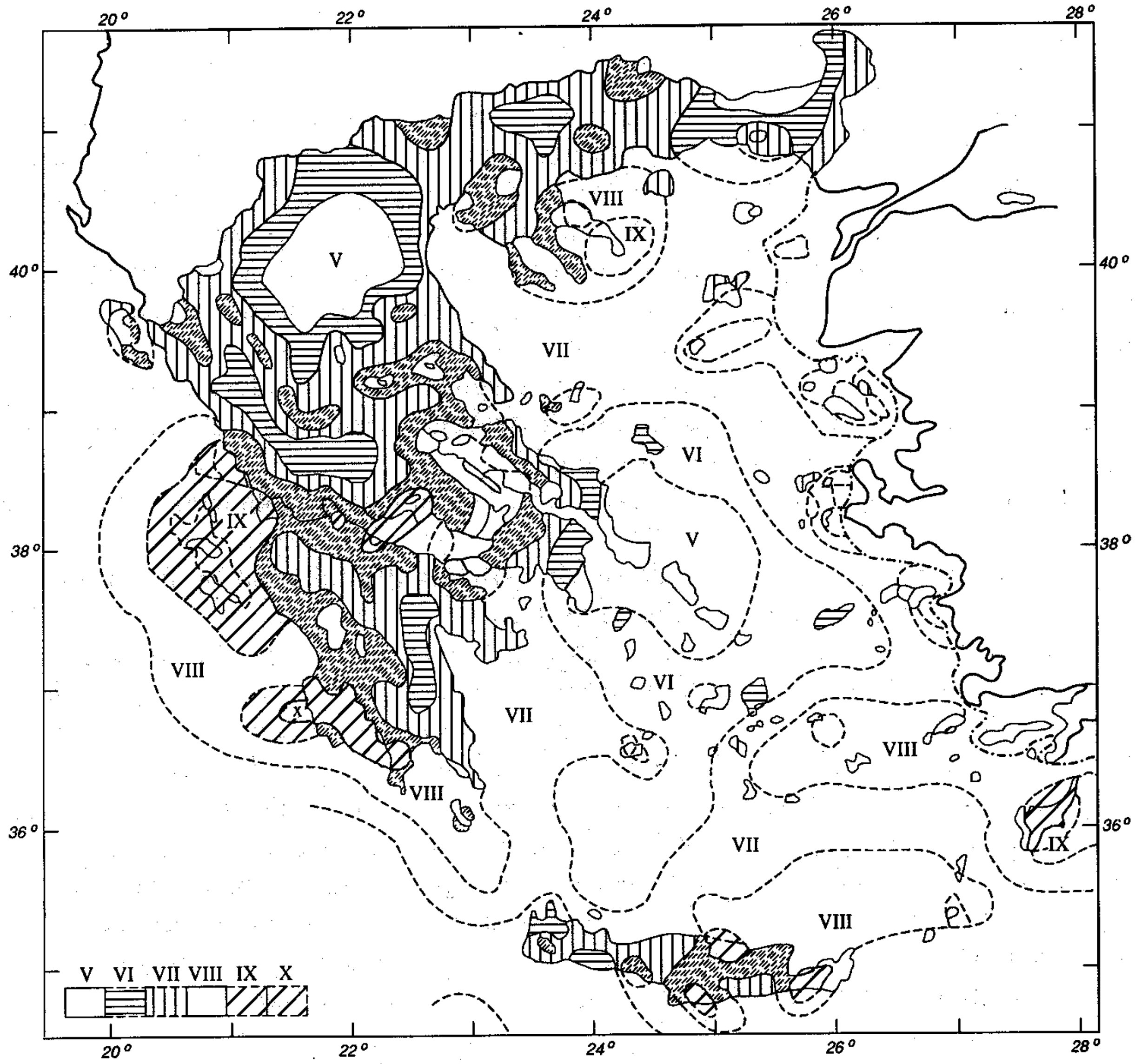

Fig.9.3. Generalised map of maximum observed epicentral intensities in Greece, 1700-1981 (Drakopoulos and Makropoulos, 1983)

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

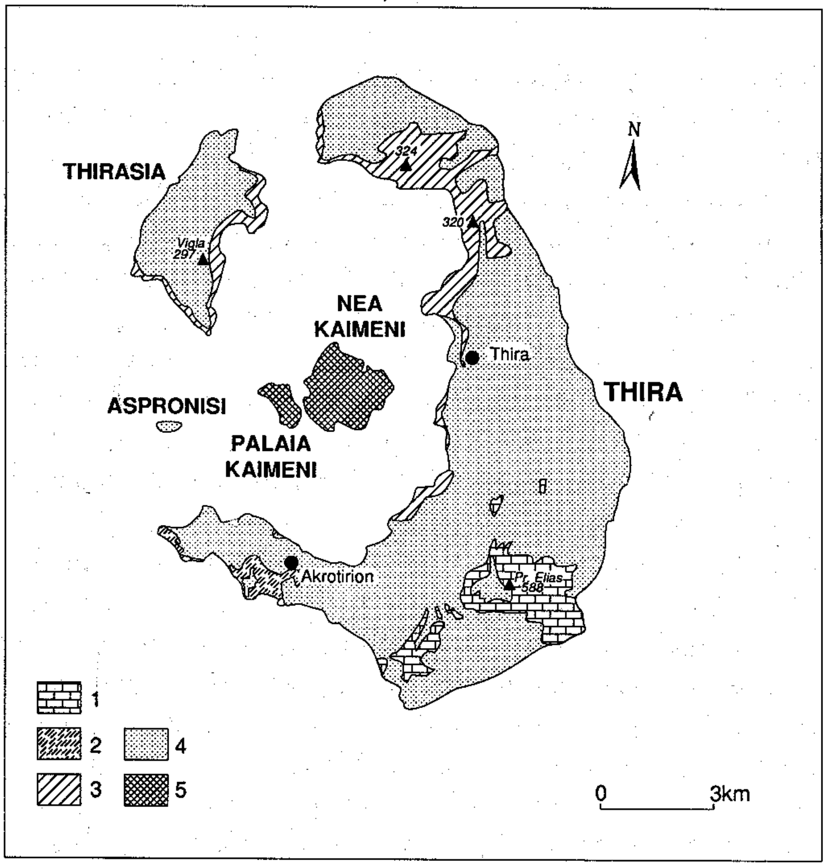

Fig.9.4. Geological map of the island of Santorini (after H.Pichler *et al.*, 1972) 1. Triassic reef limestones and Tertiary phyllites of the sedimentary basement; 2. Acid pumice tuffs and dacite lavas of the oldest (Pleistocene) eruptions; 3. Andesitic, basic lavas and pyroclastic facies produced by 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

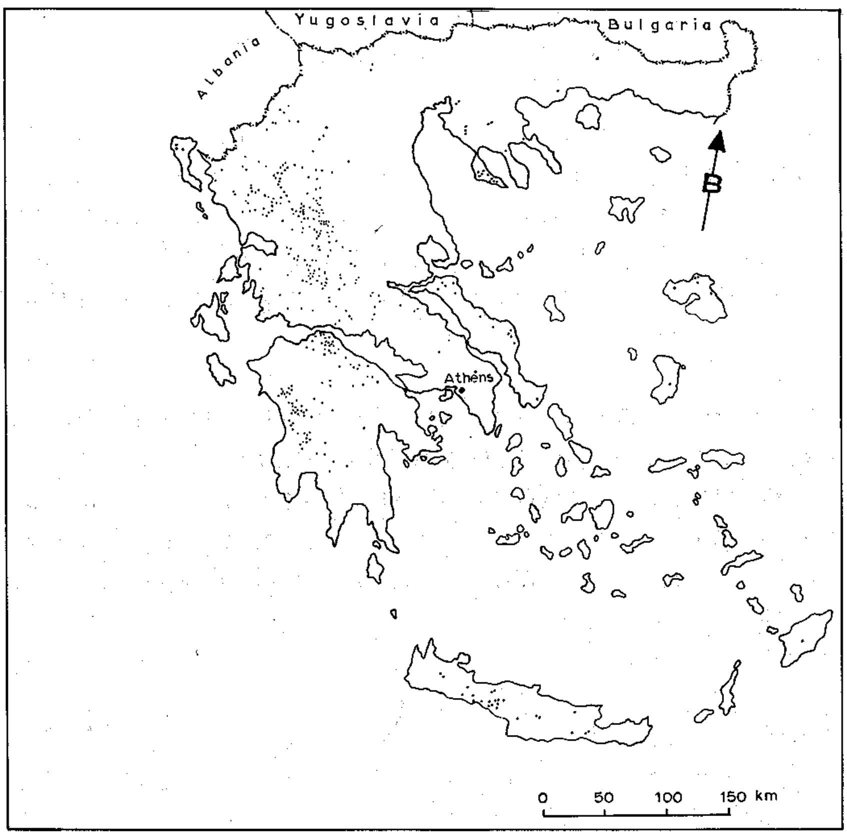

Fig.9.5. Distribution of landslides in Greece (Koukis and Ziourkas, 1991, p.51)

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

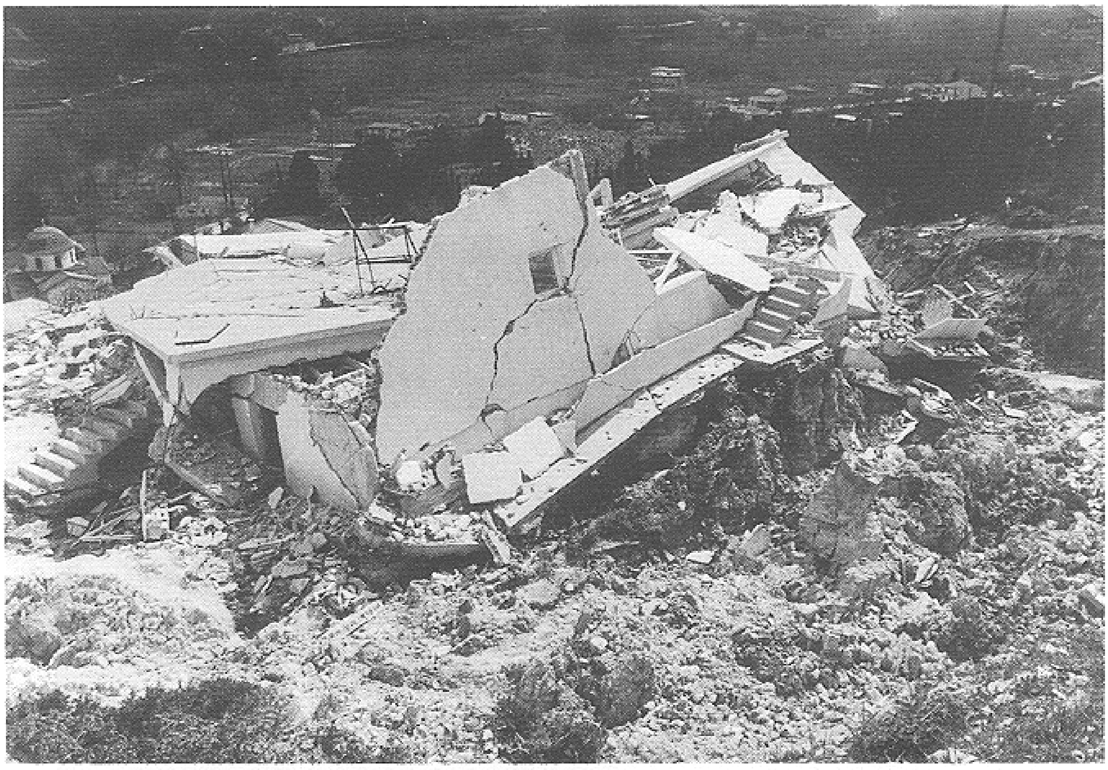

Fig.9.7.A (*upper*): Rotational slides in marly Neogene sediments, transformed into earthflows near the foot which abut on the Preveza-Igoumenitsa road, western Greece. B (*lower*): Collapsed house built on clayey-marly Neogene sediments

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

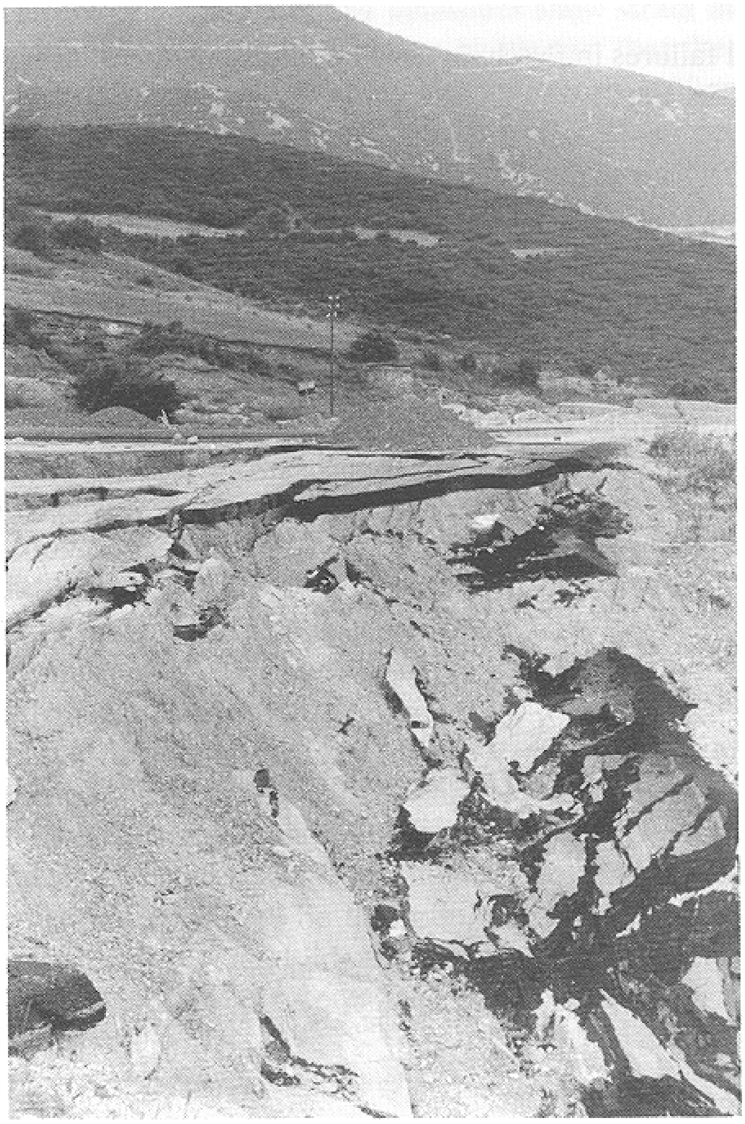

Fig.9.8. Failure of road embankment with poor foundations on weathered flysch and lacking drainage

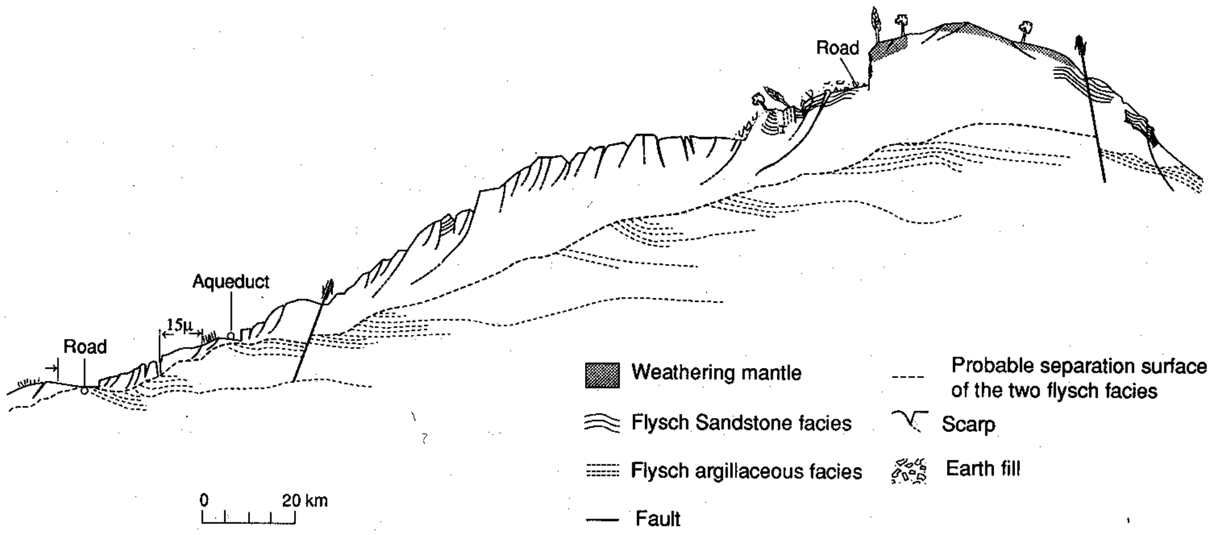

Fig.9.9. Rotational failures in flysch, in which a sandstone facies overlies an argillaceous facies (Koukis, 1988a, Fig.3)

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.

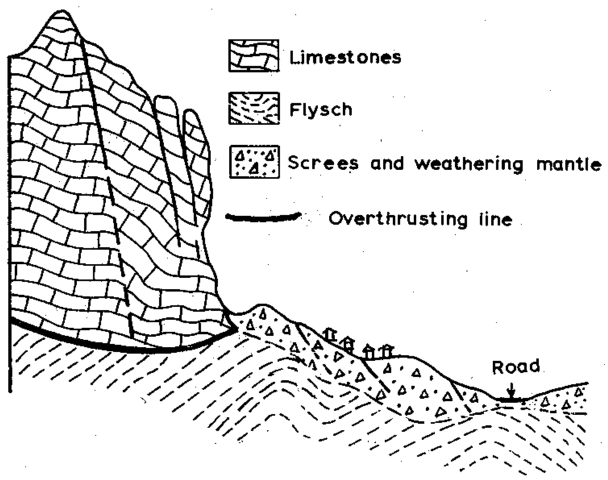

Fig.9.10. Massive limestone overthrust on flysch, a situation that threatens many villages and roads in central Greece with rock falls and slides (Koukis, 1988a, Fig.5)

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.

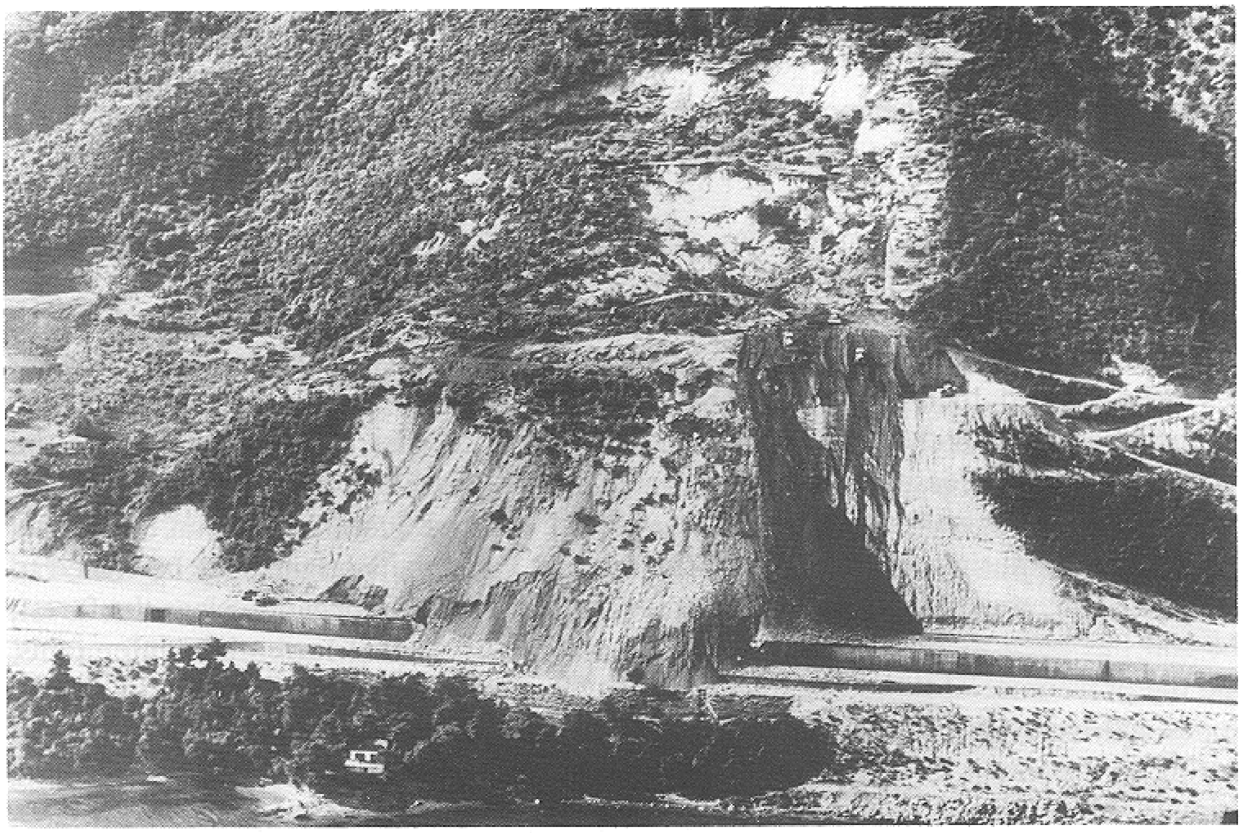

Fig.9.11. General view of the extensive landslide developed in thin-bedded Upper Cretaceous limestones and the transition zone to the flysch: Athens-Patras national road, Gulf of Corinth (Olonos-Pindos geotectonic zone). Scale is given by the house, lower left, and the three bulldozers working on the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

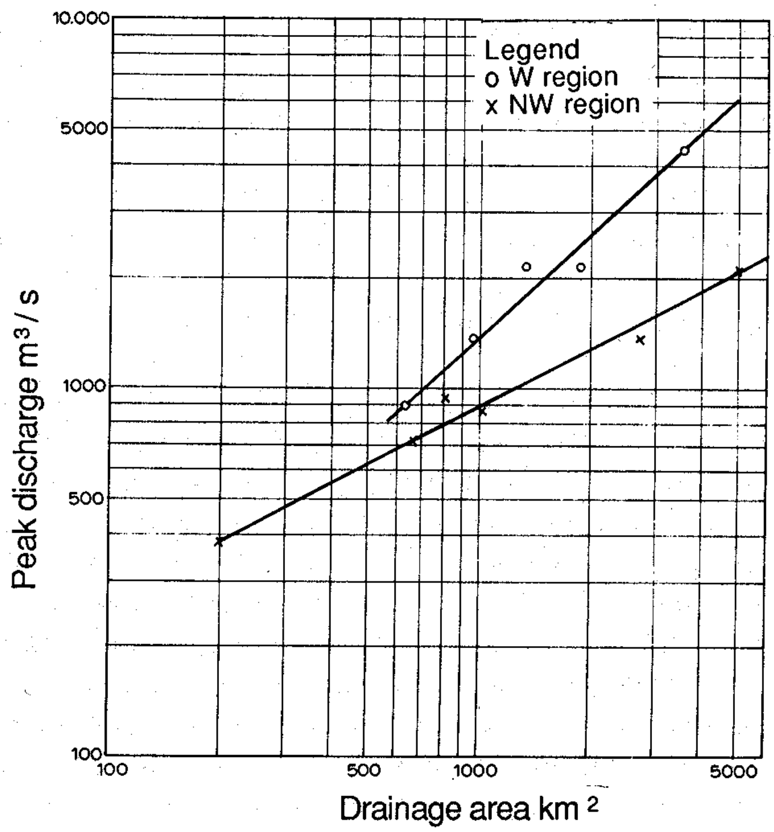

Fig.9.12. Envelope curves of peak discharge versus drainage basin area for a series of rivers in western and north-western Greece (after Mimikou, 1984)

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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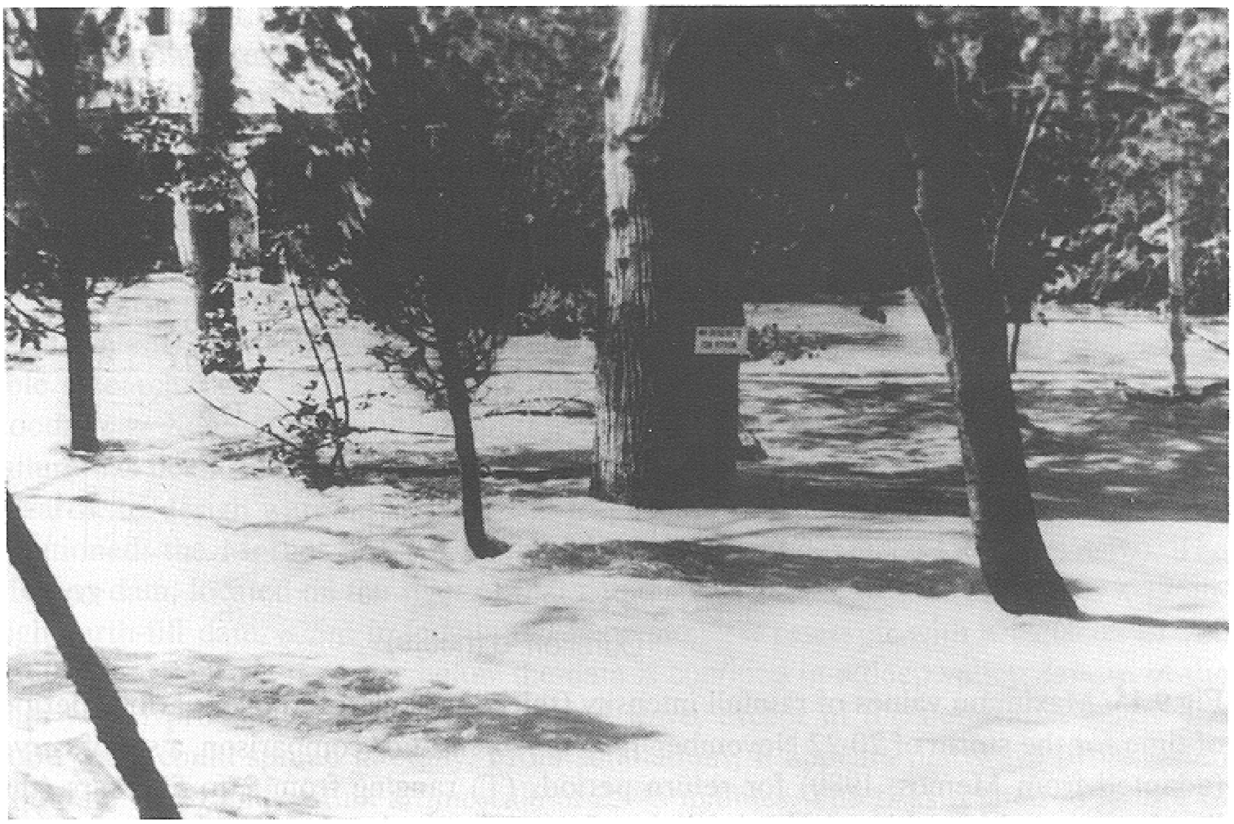
Fig.9.13. (*facing page, upper photo*) The overflow of the Pinios river at Aghia Paraskevi, Tempi ravine, during the flood of 27 March 1987. The actual river bed lies to the left of the photo. (S.Beloukas, Ministry of Agriculture)

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*)



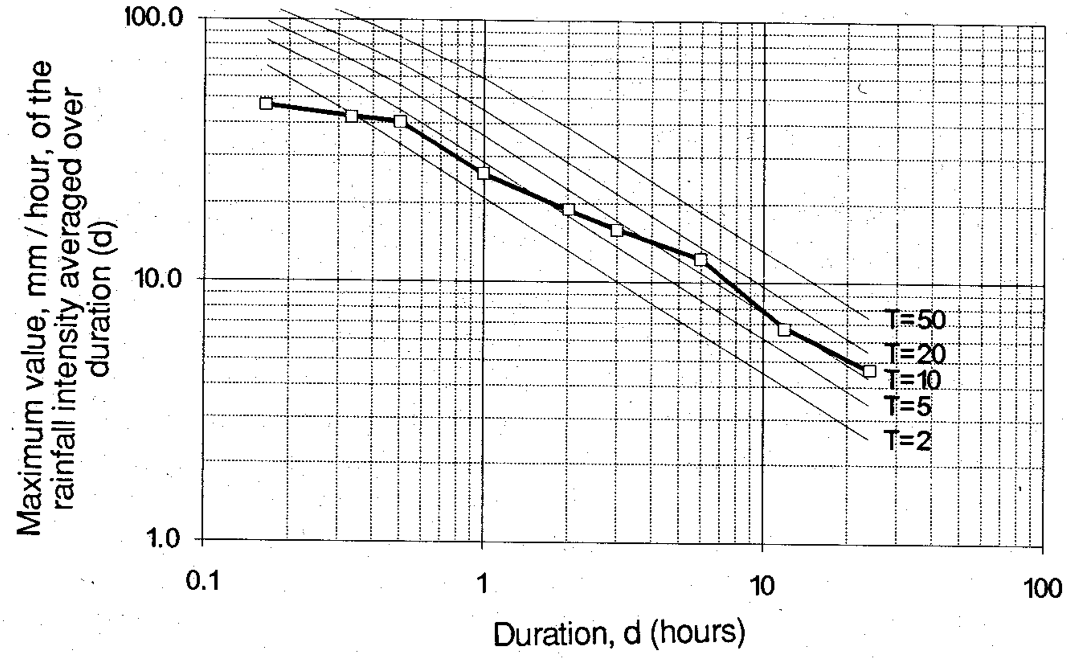


Fig.9.15. Maximum values of rainfall intensity (thick line) averaged over various periods of time for the storm of 20-22 November 1993 in Athens. For comparison, a set of curves (adapted from Memos, 1980) for return periods (T) ranging from 2 to 50 years (thin lines), extracted from historical rainfall 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.

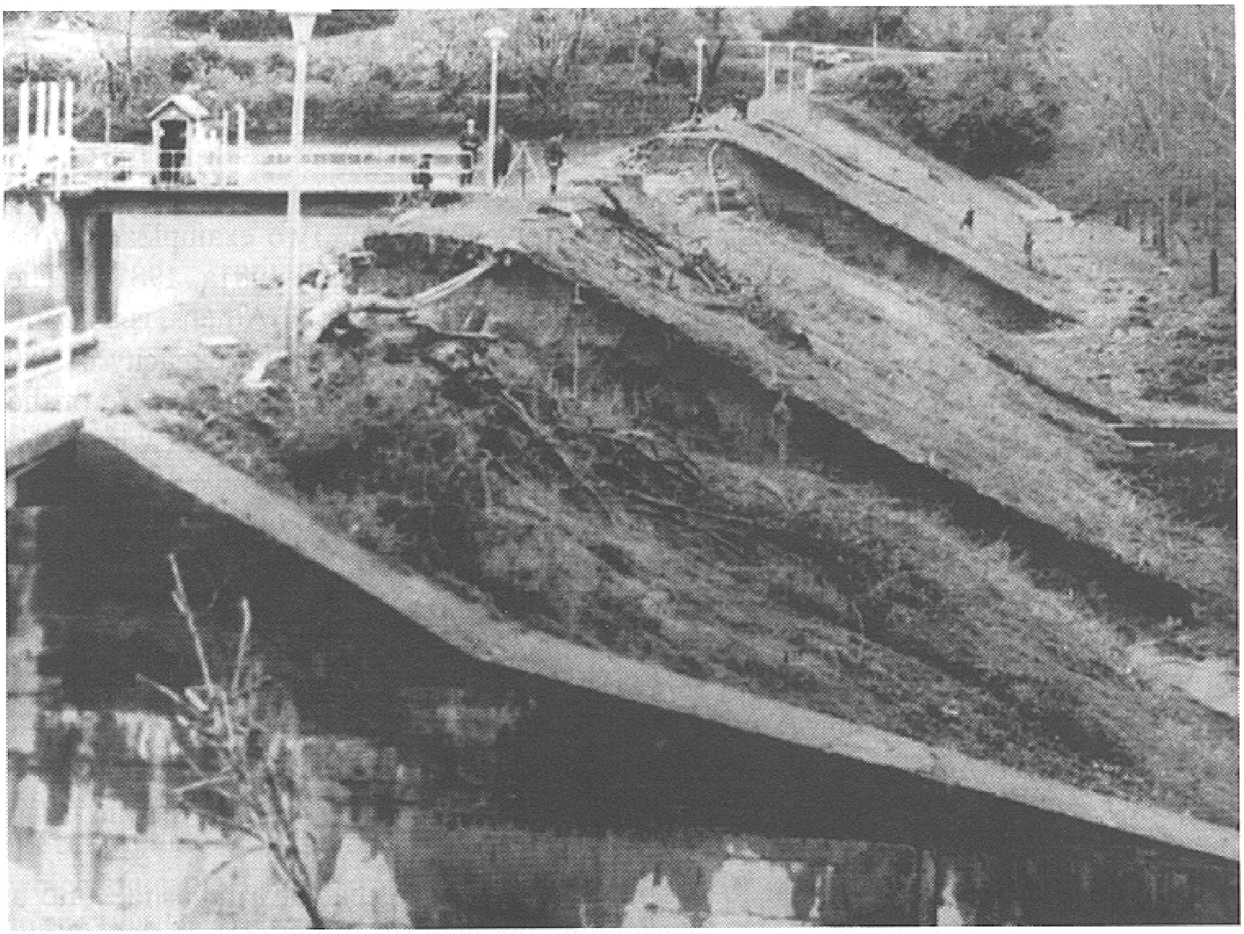


Fig.9.16. A view of the breaches in the Agras dam caused by the flood of 18-19 November 1979

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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