EARTHQUAKE RISK ASSESSMENT & MANAGEMENT

CASE STUDY: CYPRUS

A thesis submitted for the degree of Doctor of Philosophy in the Faculty of Engineering of the University of Sheffield

by

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Dedicated to my parents Yiangos and Androulla,

Αφιερωμένο στους γονείς μου Γιάγκο και Ανδρούλλα,

and to my grandparents who, although they never had the opportunity themselves, enabled others.

και στους παππούδες και γιαγιάδες μου, που έστω και αν δεν είχαν οι ίδιοι ποτέ την ευκαιρία, έδωσαν την ευκαιρία σε άλλους.

ABSTRACT

Earthquakes are amongst the worst natural disasters on Earth, resulting in an annual average of around 10,000 fatalities last century and progressively increasing in the amount of economic damage they cause, reaching US $20 billion per annum this decade.

The mitigation of the unwanted consequences of earthquakes is normally achieved by Risk Management Strategies (RMS), which rely on the development of Earthquake Risk Assessment (ERA) techniques. This thesis aims to develop a framework for ERA for medium seismicity regions that incorporates the spatial aspects of the hazard and risk evaluation. The framework is used to undertake ERA for the island of Cyprus, and the information is used to propose RMS.

The ERA framework relies on comprehensive data on the location, value and vulnerability of buildings and the population distribution. These data were collected from the various Cyprus Government Departments. Various hazard and attenuation models are examined, and the effect of their variability is taken into account through Monte Carlo simulations.

The estimated annual risk for Cyprus is just below £10 million CY. This value was estimated based on the use of the re-appraised historical data for the past–century. Comparisons with other seismic hazard assessment methods, such as recurrence relationships, have revealed that, without a spatial distribution model, such approaches are unsuitable for ERA.

Though the maximum intensities predicted are in line with the ones that underpin the aseismic code of Cyprus (CCEAA-CFEE, 1994), the predicted design accelerations are higher than given in the code. Hence, new seismic accelerations are proposed. Despite that, the current reduction in risk is comparable to the additional cost of aseismic design.

Seismic retrofitting was also examined and it was found that as part of a general modernisation scheme seismic upgrading is cost effective. However, whatever the state of the building, it is recommended that earthquake insurance should be made mandatory. The current seismic insurance rates appear to be fair, though they seem to underestimate the risk in the areas of high seismicity. The number of likely human losses is also estimated.

This study concludes that the result of ERA is heavily dependent on the models and data used, and both require constant updating for the ERA results to remain meaningful.

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ABBREVIATIONS

CY	Cyprus
EMR	Eastern Mediterranean
EQ-RACY	Earthquake Risk Assessment Cyprus
ERA	Earthquake Risk Assessment
GIS	Geographical Information Systems
HAZUS®	Hazards United States
IDNDR	International Decade of Natural Disaster Reduction
IPRG	Institute for Petroleum Research and Geophysics
ISC	International Seismological Centre
MDR	Mean Damage Ratio
MFR	Mean Fatality Ratio
MIR	Mean Injury Ratio
MMI or IMM	Modified Mercalli Intensity
PERA	Probabilistic Earthquake Risk Assessment
PGA	Peak Ground Acceleration
PGV	Peak Ground Velocity
POE	Probability Of Exceedance
PSH	Probabilistic Seismic Hazard
PSHA	Probabilistic Seismic Hazard Assessment
RADIUS	Risk Assessment tools for Diagnosis of Urban areas against Seismic disasters
RC	Reinforced Concrete
RELEMR	Reducing Earthquake Losses in Eastern Mediterranean
RMS	Risk Management Strategies
SBI	Seismological Bulletin of Israel
UNESCO	United Nations Educational, Scientific, and Cultural Organisation
USGS	United States Geological Survey

NOTATION

α	Acceleration
σ	Standard deviation
d	Horizontal displacement
E	Energy factor (ergs)
h	Focal depth
I	Intensity
I_{MM}	Modified mercalli intensity
M	Magnitude
m_b	Body wave magnitude
M_L	Local magnitude
M_S	Surface wave magnitude
M_W	Moment magnitude
N	Number of earthquakes with magnitude equal to or greater than the specified M_S
R	Source-site distance
Rcer	Hypocentral distance
S	Soil characterisation

INTRODUCTION

1.1 BACKGROUND

Since the beginning of civilisation, millions of people and thousands of structures around the world have perished in earthquakes. Unfortunately, short-term earthquake prediction is still an impossibility. However, there are methods available for the approximate long-term prediction of earthquake events. Earthquake risk assessment (ERA) is necessary to develop risk management strategies (RMS) usually used to mitigate against the undesirable results of seismic actions.

Insurance companies carry out ERA to calculate the appropriate premium rates or the probable maximum loss that would be incurred in the event of a catastrophic earthquake. ERA is also performed as part of urban earthquake risk mitigation programs, the main aim of which is to reduce the fatalities, injuries, construction damage and other economic losses caused by an earthquake.

ERA provides a means of assessing and comparing various RMS, such as aseismic design measures for new buildings, remedial measures, insurance law etc. Alternative methods of ERA and management are discussed further in the thesis. One way of achieving the assessment and comparison of the various RMS is by predicting the potential patterns of future events and developing strategies which will help manage or mitigate their possible consequences.

The island of Cyprus, which is situated in the Eastern Mediterranean, lies within the second largest earthquake-stricken zone of the earth. Throughout its history it has suffered significant damage due to earthquakes. Since 1995, 12 earthquakes, with magnitude $M_S \geq 5.0$ on the Richter scale, have hit the island of Cyprus, causing two deaths, injuries, structural damage and economic losses. This has increased concern amongst the people of Cyprus and highlighted the need for improved risk assessment and management. The first basic seismic provisions were introduced in 1986. In 1994 a formal and comprehensive aseismic code was introduced in the island (CCEAA-CFEE, 1994). However, these aseismic measures were introduced without any comprehensive earthquake risk management studies.

Therefore, the aim of this research is to provide decision-making risk management information for the island of Cyprus, which will help quantify the effect of current strategies and compare alternatives. This will be achieved by implementing a probabilistic ERA method in a computer model and utilising a Geographic Information System (GIS) for presenting the various thematic maps.

1.2 RESEARCH OBJECTIVES

The direct objectives of this research were:

1. To develop an ERA framework that incorporates the spatial and probabilistic aspects of seismic hazard and risk evaluation
2. To apply the framework to the island of Cyprus by producing spatial and probabilistic models for seismic hazard, building and population density, vulnerability, and geology
3. To assess various RMS such as:
   a. Prevention: Identification of high risk areas and recommendations of no-build zones
   b. Mitigation: Introduction of aseismic regulations
   c. Spreading of Risk: Estimation of the annual Insurance premiums
   d. Intervention: Comparison of the cost of strengthening existing buildings to the earthquake risk
   e. Preparedness & Emergency Response: Formulation of any contingency and long-term planning suggestions for preventing loss of life and economic losses

The risk management strategies examined or developed will eventually be proposed to the appropriate authorities of the island.

1.3 STRUCTURE OF THE THESIS

To achieve the above objectives an interdisciplinary approach is required.

Hence, Chapter 2, which presents the review of the literature, is divided into four main sections. Section 2.2 includes a brief summary of the seismological aspects, with a more detailed account on the phenomenon of earthquakes presented in Appendix A. The various methods of ERA and their advantages and disadvantages are examined in Section 2.3 and the options for Risk Management are presented in section 2.4. Finally the regional characteristics of Cyprus (seismicity, geology, etc) are covered in section 2.5.

Chapter 3 presents detailed information on the major aspects involved in the calculation of the earthquake risk and the parameters dealing with the estimation of human losses. This chapter has been divided into 4 sections (Hazard, Vulnerability, Value of elements at risk and Fatalities and Injuries). In particular it reports the work done on the seismicity analysis of Cyprus and introduces the derivation of a new recurrence relationship. Furthermore, it quantifies and explains how the Hazard, Vulnerability, Value of elements at risk and Fatalities and Injuries will be utilised in the computer model.

The development of the EarthQuake Risk Assessment-Cyprus (EQ-RACY) model and the analysis of the process, can be found in Chapter 4. This chapter also includes a section on the modification and improvements of the model as well as an account of the validation studies.

Chapter 5 presents the analytical investigation and the parametric studies performed in an attempt to establish the effect of the variability of the parameters involved in the estimation of the earthquake risk on earthquake damages, economic losses, and casualties. The results of these parametric studies as well as the limits and ranges adopted for the probabilistic simulations proposed are also presented in this chapter.

Chapter 6 initially presents the results of the Monte Carlo simulations for Probabilistic Earthquake Risk Assessment (PERA). Two approaches to seismic hazard determination are also proposed and tested for their applicability in the assessment of the earthquake risk. Finally several RMS are discussed and relevant suggestions are made.

Overall conclusions of the study are made in chapter 7 and recommendations for further research are suggested.

LITERATURE REVIEW

2.1 INTRODUCTION

Due to the multidisciplinary nature of this research the literature review is separated into 4 topic areas: Seismological Aspects, Earthquake Risk Assessment (ERA), Risk Management, and Parameters affecting the earthquake risk in the region of Cyprus. In the following sections only the most pertinent information is presented and the more general background information is given in Appendix A. This appendix has several sections to which the reader will be referred to as necessary.

After these disciplines are addressed the need for this research will be discussed and justified.

2.2 SEISMOLOGICAL ASPECTS

An earthquake is the violent shaking of the ground, which is the result of the mechanical failure of a brittle layer in the earth's strata. The ground shaking can lead to the collapse of man-made structures or surface natural structures. Throughout history earthquakes were responsible for significant loss of life and damage to many civilisations.

Unlike most natural disasters, earthquakes cannot be predicted in the short-term with accuracy. In 1975, the Chinese successfully predicted an earthquake of magnitude 7.3 on the Richter scale and two days before the event at Haicheng, 90,000 residents were evacuated (Bolt, 1978). When the earthquake struck there were only structural losses (90 percent of the city's buildings were either damaged or destroyed). However, 18 months later they failed to predict the Tangshan earthquake (160 kilometres east of Beijing) with a magnitude of 7.6, which caused the largest number of earthquake related fatalities ever (estimated more than 500,000 fatalities) (Bolt, 1978).

Short-term prediction, if reliable, may prove useful in protecting the population, but cannot help reduce the risk to the building stock, which still has to be designed to resist the seismic force (Coburn and Spence, 1992). Hence, for engineering purposes, long-term prediction techniques are required to ensure that informed risk assessment influences the design of buildings. Long-term prediction of earthquakes is based on probabilistic approaches and on the study of the historical seismicity of an area. Earthquake hazard prediction models are based on two basic assumptions. The first assumption is that the cumulative frequency of earthquakes greater than a specific magnitude can be determined for a specific area based on past seismicity (Gutenberg and Richter, 1965 in Dowrick, 1987). If the frequency at which earthquakes have occurred in the past is known (either from historical records or geological records), one can make generalised statistical statements about the probabilities of earthquakes occurring in the future. For example, it can be said that an earthquake of magnitude 6.0 on the Richter scale is expected in Cyprus once every 36 years (Grambis, 1997). The second assumption is that earthquakes obeying that relationship will occur randomly in time within the given space. Both assumptions are recognised to have limitations (Dowrick, 1987).

The purpose of this research is to adopt and modify existing long term earthquake prediction series or models so as to simulate new series of earthquakes of various magnitudes and epicentres which might occur through a pre-defined period of time in a given space. The possible damage caused by those earthquakes may be estimated by taking into consideration the effect of geology on the attenuation of the seismic waves, the vulnerability and the distribution of the building stock as well as the economics involved.

Some general information relating to the seismological aspects of earthquakes is given in Section 1 of Appendix A. This information is of relevance to the calculations later on, dealing with:

1. The selection of earthquakes for the database of seismic events
2. The relationship between various magnitude scales
3. The relationship between magnitude and energy
4. The relationship between magnitude and intensity
5. Attenuation equations and the effect of depth and geology
6. Vulnerability
7. Seismic Hazard

2.3 EARTHQUAKE RISK ASSESSMENT

2.3.1 INTRODUCTION

Earthquakes are amongst the worst natural disasters on Earth, in terms of fatalities and economic loss. The technique usually adopted by engineers and decision-makers to mitigate the undesirable results of such disasters is ERA. During the last two centuries the urbanisation of seismically active areas has increased significantly and ERA has become progressively more important.

ERA can be defined as the determination of the potential destructiveness of an earthquake before it strikes a specified region and of the actual destructiveness after it strikes (Hays, 1994).

ERA forms the basis for the calculation of premium rates for earthquake insurance purposes and for the determination of the range of the probable maximum loss that would be incurred in the event of a catastrophic earthquake (Rauch and Smolka, 1992). ERA is also performed as part of earthquake risk mitigation programs in urban areas, the main aim of which is to reduce the fatalities, injuries, construction damage and other economic losses caused by an earthquake (Dowrick, 1987; Hays, 1994). In this respect it affects the data and safety factors used in engineering design.

2.3.2 SEISMIC RISK

The Seismic Risk in a region defines, monetarily, the amount of prospective damage inflicted on structures by an earthquake. The assessment of the Seismic Hazard and its mapping are the most important steps towards a general evaluation of the Seismic Risk.

The Seismic Hazard relates to all physical phenomena which are a consequence of the earthquake (such as strong ground motion, liquefaction, tsunamis, landslides, or even induced fires) that can affect the infrastructure and other aspects of human interaction with the environment. Therefore, if an earthquake was to occur in an unpopulated (dessert) region its seismic risk would be zero whatever its intensity and seismic hazard may be.

According to Dowrick (1987) Seismic Risk can be defined as:

$$\text{SeismicRisk} = (\text{SeismicHazard}) \text{ x } (\text{Vulnerability}) \text{ x } (\text{Value}) \quad \textbf{(2.1)}$$

where: Vulnerability is the amount of damage induced by a given degree of hazard, and expressed as a ratio of the Value of the damage to the total cost of the item under consideration.

This relationship is also represented graphically in Figure 2.1.

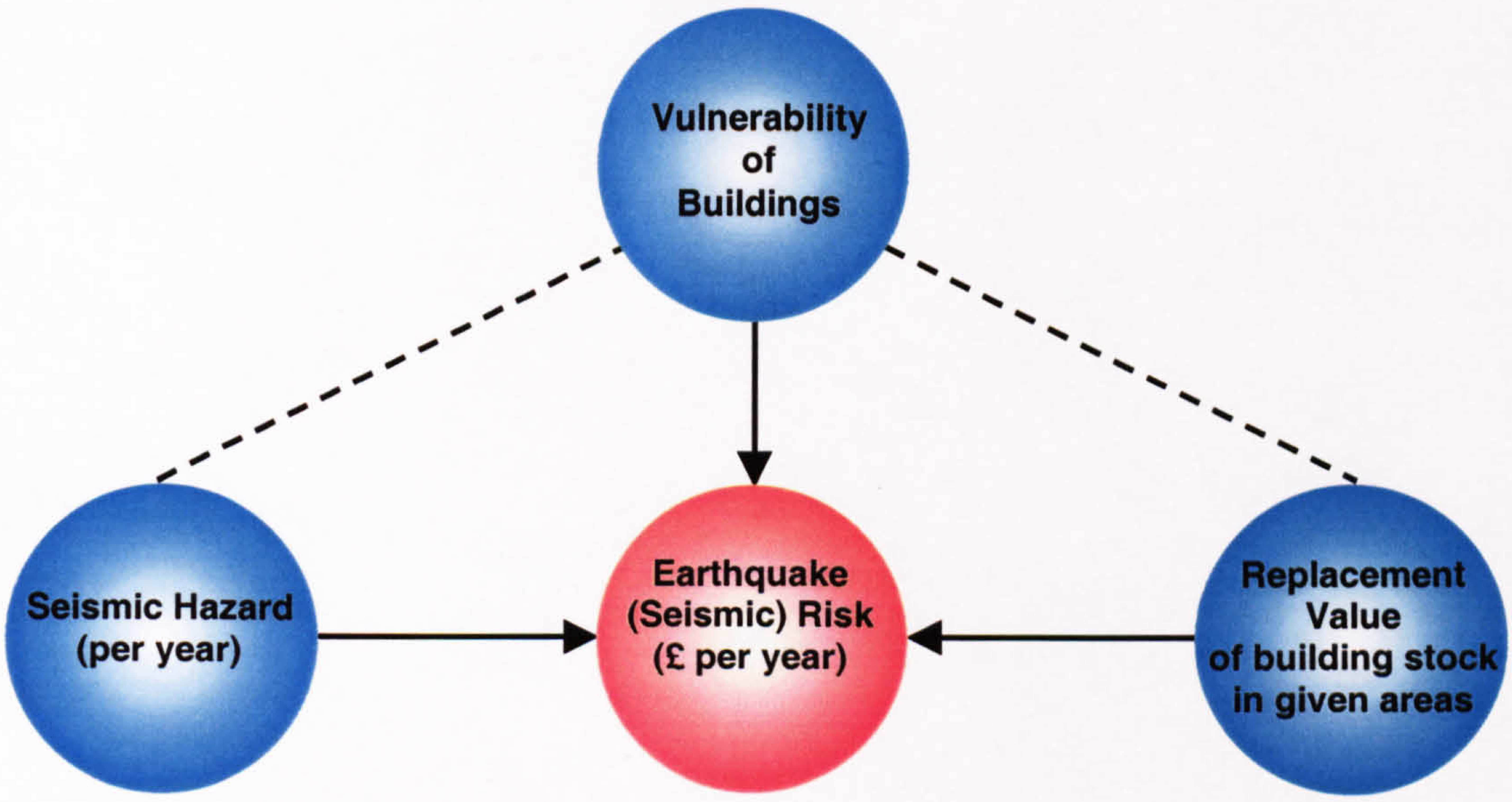


Figure 2.1. Earthquake Risk Assessment

A more detailed description of the Seismic Risk, R, is the one given in Equation 2.2.

$$R = \sum_{i=1}^{n} \sum_{j=1}^{m} (H_i * V_{ij}) * C_j \quad \textbf{(2.2)}$$

where: H_i is the Seismic Hazard (i=1 to n).
V_{ij} is the Vulnerability, of each element j at risk for each hazard i.
C_j is the Value of element j at risk, e.g. buildings, economic activities, public services etc, in the area under consideration.

However, there is no general consensus of opinion regarding the elements involved in a risk assessment (i.e. Seismic Hazard, Vulnerability and Value). Other authors (Hays, 1994; Menoni et. al, 1998), have suggested different ideas introducing new elements or suggesting a different way of presenting the three basic elements.

Hays (1994), suggested that the determination of the seismic risk requires four elements. These are the temporal and spatial characteristics of the hazards, the exposure (i.e. inventory of buildings and lifeline systems), the location of buildings and lifelines relative to the disaster agents, and the vulnerability (i.e. expected loss of value or function). The accuracy of these determinations is reduced due to the uncertainty in the knowledge base on temporal and spatial parameters for each of the elements mentioned above (Hays, 1994).

Furthermore, the Seismic Risk has also been defined as the convolution of three factors: Seismic Hazard which includes all direct physical effects produced by an earthquake; Induced Physical Hazard, refers to those events, like landslides, that might be triggered by ground motion; and Systemic Vulnerability, refers to the vulnerability of urban and regional systems which cannot be considered only as the sum of the vulnerability of exposed structures (Menoni, et. al, 1998).

However, despite the availability of different representations suggested for the seismic risk it is widely accepted that the basic parameters required for the assessment of risk are hazard, vulnerability and value. This research will follow the original definition, mainly due to the lack of adequate data required for the implementation of any of the other more complex definitions suggested above.

2.3.3 SEISMIC HAZARD

The probability of seismic shaking reaching or exceeding a certain magnitude (or macroseismic intensity) during a reference period determines the Seismic Hazard for a particular area. Other parameters, which can also determine the Seismic Hazard, are maximum acceleration, velocity or displacement.

2.3.3.1 EVALUATION OF SEISMIC HAZARD

Seismic Hazard Assessment (i.e. identification of the spatial and temporal distribution of the disaster agent) can be made on national, regional, urban and site specific scales (Figure 2.2).

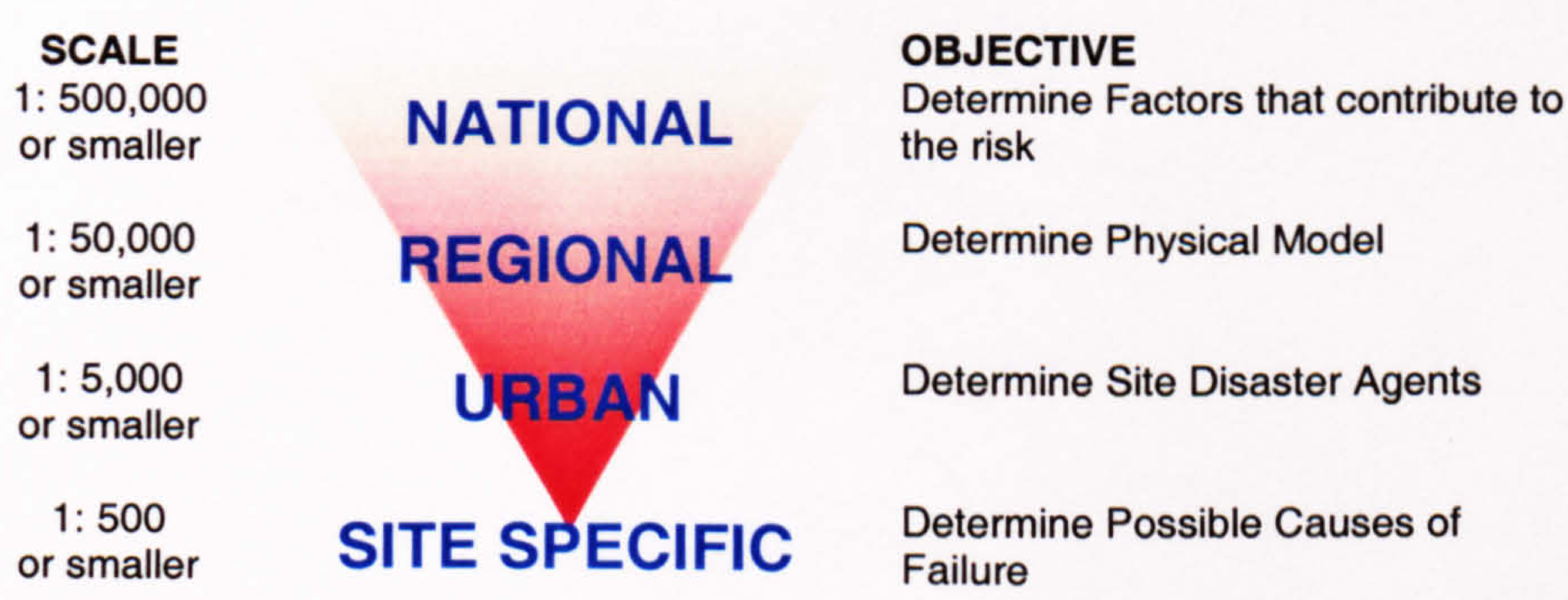


Figure 2.2. Scale of investigation (after Hays, 1994)

The potential phenomena generated by an earthquake are ground shaking, liquefaction, landslides, tectonic deformation, surface fault rapture, tsunamis, release of toxic materials, fire and aftershocks. These are described in Section 1.2 of Appendix A.

There are various methods that have been used to assess the Seismic Hazard for a given region.

1. Observational
2. Deterministic
3. The Statistical
4. Probabilistic Seismic Hazard Assessment (PSHA)
5. Time dependent

All of these methods have been used by engineers in order to obtain the ground motions or intensity distributions, at the sites under consideration, and employ those results in earthquake design calculations.

Furthermore, insurance companies have used the PSHA method, in an attempt to calculate appropriate premium rates for earthquake insurance or to determine the range of probable maximum loss that would be incurred in the event of a catastrophic earthquake.

The following sections give an introduction to these methods, highlighting their advantages and disadvantages.

OBSERVATIONAL METHOD

Early attempts at seismic hazard assessment were based on the collection of past observations. Initially, by using the historical record of an area, a spatial distribution of earthquakes was created. This enabled the differentiation of zones with more frequent earthquakes from those with few. This approach has been refined through the identification of the actual effects of earthquakes in terms of intensity distribution and the production of maps displaying the maximum observed intensity over the specific historical period for the area under consideration. The usefulness of this map is to illustrate what had happened in the past. Nevertheless, it cannot demonstrate the possible outcome of an earthquake that might occur, which would not necessarily be a repeat of a historical event.

For design purposes a way to overcome this limitation, proposed by Musson (1998), is to take the maximum intensity and add a safety margin, such as plus one intensity degree. Therefore, the design values would in general be quite conservative.

The observational method is simple and, hence, can be used in many areas of the world where there are sufficient historical data.

For the purposes of this research the observational method was used at the early stages in the study of the seismicity of Cyprus. This enabled the identification of the non-uniformity of the spatial distribution of the earthquake events in the area of Cyprus and highlighted the areas of high seismicity which required more detailed examination.

DETERMINISTIC METHOD

Deterministic processes produce patterns with total certainty, since the outcome can be specified with very high likelihood. Deterministic Seismic Hazard goes beyond observations of effects in an attempt to look at the causes of seismicity. The objective of this method is to identify the worst possible outcome of an earthquake.

The Deterministic method is suitable for the seismic hazard assessment of a specific structure. Margottini (1992), suggested that once the seismic source is identified, the nearest fault to the specific site is located. Then the maximum potential earthquake that could happen on this fault can be calculated either by the use of the historical record of the area under consideration or by the use of the geophysical characteristics of the fault (i.e. size and nature). By assuming that this maximum earthquake will happen at the closest point to the site the resulting ground motion (maximum peak ground acceleration - max α, maximum peak horizontal displacement - max d etc) can be calculated. After determining the vulnerability, the expected damage can be estimated.

This deterministic method is relatively easy to perform. When the seismic hazard assessment of a specific site is required, this method is considered quite adequate. However, the location of the active faults is not always known and, furthermore, it is quite easy to end up with over-conservative hazard values, since the probability of occurrence of the largest possible earthquake on a particular fault may be insignificantly small. On the other hand the possibility of occurrence of a larger earthquake than the one anticipated, during the lifetime of the facility will always exist. One could then suggest that this would lead from over-conservatism to under-conservatism. Nevertheless, the simplicity that characterises this method makes it attractive.

Additionally, it could be considered as quite sufficient for an initial approximation of the seismic hazard for structures where the consequences of failure are not too great.

The deterministic approach has already been used for the assessment of the seismic hazard to accommodate the input for scenarios by selecting a specific ground motion (Menoni, et al., 1998). However, this method has not been adopted in this research since the aim is to assess the earthquake risk of the whole island rather than of a specific structure. Nevertheless, the results of this research (i.e. possible identification of high seismic risk in areas with significant structures such as water dams, airports, hospitals and military facilities) might lead to further studies which could include the implementation of a deterministic approach.

THE STATISTICAL METHOD

This method involves the application of statistical methods to the observed earthquake record in an attempt to calculate the probability of occurrence of future events. The generation of earthquakes falls under the general category of stochastic phenomena. An analogous phenomenon to earthquakes is the phenomenon of floods and Gumbel (1954) developed the theory of forecasting floods based on the extreme values. The statistical method relies on the theory of extreme values.

In simple terms, this theory requires the knowledge of the annual, extreme (i.e. highest observed) earthquake magnitude or ground motion or intensity (according to the specific needs of the calculations) at the specified site. The application of the statistical properties of distributions of extreme values will enable the estimation of the probability of the annual maximum value within a specified return period.

For the theory for the occurrence of large earthquakes to apply, the observed largest magnitude values of earthquakes are assumed independent of each other and the prevailing geotectonic conditions of earthquake generation are considered to remain constant in time. Although aftershocks are a clear example of the dependency between earthquakes, it is accepted that large earthquakes are really independent events. The first assumption therefore is satisfied. World-wide observations prove that seismicity differs from region to region. Both the magnitude and the frequency of occurrence of earthquakes differ from one region to another, i.e. there are regions both on a global as well as local scale, which differ systematically regarding their seismicity and seismic hazard. However, because the geotectonic setting of the same region changes insignificantly or very little with time, it follows that the second assumption is fulfilled.

The advantage of the theory of extreme values is that it does not require the analysis of the complete earthquake record. It uses the sequence of earthquakes obtained from the relationship between the highest magnitude, or ground motion, or intensity values and a set of fixed intervals (Dimiskovska, 1995). However, this could also be considered as the disadvantage of this method. Most of the data is discarded and only the few extreme values are used. This method is accompanied by an uncertainty on whether a small sample of the data gives better prediction than one which uses a complete set of data (Musson, 1998). Moreover, depending on the time period covered by the earthquake catalogue only the earthquakes with return periods within the range of the catalogue can be calculated with reasonable confidence. If earthquakes with longer return periods are required then the method becomes fairly unreliable.

For the specific case of Cyprus this method will not be adopted since the number of reliably assessed extreme events within the historical record of the island is rather limited and any forecasts would not be representative of the expected seismicity.

PROBABILISTIC SEISMIC HAZARD ASSESSMENT (PSHA)

PSHA methods involve probabilistic modelling and statistical analysis. These methods were first developed in the late 1960s (Cornell, 1968, in Grunthal, et al., 1995; Cornell, 1971) and are now used regularly (Margottini, 1992; Bottard and Gariel, 1995; Grunthal, et al., 1995; Lenhardt, 1995).

The probabilistic approach proposed by Cornell (1968) includes the following steps:

1. the geometrical identification of seismic sources (i.e. define seismogenic units either area source zones or individual faults);
2. the development of models describing the seismicity characteristics of the sources (i.e. quantify their magnitude recurrence (M-N) relation, earthquake activity);
3. the determination of attenuation laws for the relevant parameters between the sources and the site (i.e. quantify their Intensity (I) -Distance relation, or peak ground acceleration (PGA) (α) -Distance relation);
4. the addition of the contribution of all the individual sources likely to influence the distribution of the chosen parameters on the given site.

These steps are presented graphically in Figure 2.3.

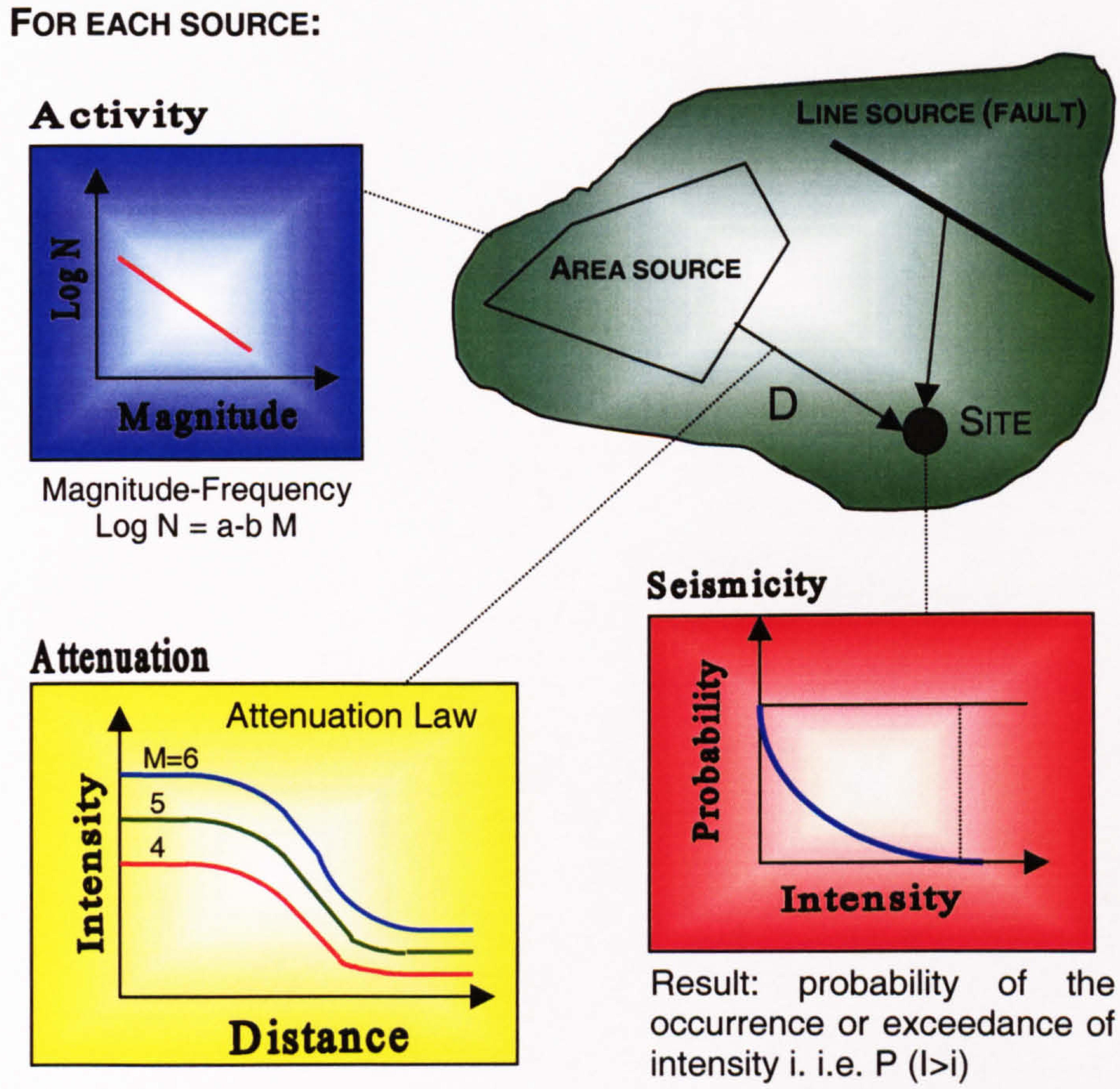


Figure 2.3. A schematic illustration of the standard approach for seismicity assessment, allocating seismic activity to known sources (after Schmid, et al., 1995; after Grunthal, et al., 1995)

The main aim of this method is to estimate the probability that a particular relevant parameter (i.e. acceleration or intensity) will be exceeded during a specified period of time at the site under consideration (Sobaih, et al., 1994). By estimating the probabilities of the other intensity values or PGA, for various time periods, a complete account of the hazard at the specific site can be obtained.

Since they were first developed (point–source model) probabilistic approaches have been widely used with only slight modifications, such as the fault rupture model (Der Kiureghian and Ang, 1977, in Jiang, 1991) and elliptical tectonic model (Jiang, 1991). These models differ in the representation of the source (lines or regions on the geographical plane) and in the definition of distance from the earthquake to the site (epicentral distance, focal distance, or distance to the rupture zone) (Figure A-3 in Section 1.1 - Appendix A).

The full representation of the seismic hazard is known as a seismic hazard curve, which basically represents the decreasing probability of increasingly larger intensities or peak ground accelerations (i.e. I or PGA versus annual probability of exceedance).

The probabilistic approach also assumes that earthquake events are temporally, spatially and intensity independent. In order to describe the temporal, spatial and strength distribution of the earthquake activity the stationary Poisson process, the identification of potential seismic sources and the Gutenberg-Richter's magnitude-frequency relationship (in Ambraseys, 1992) are applied, respectively. In other words, the earthquake occurrence in time can be modelled as a Poisson process, and the distribution of seismic activity over a seismogenic source is homogenous (i.e. earthquakes have an equal probability of occurring at any point within this zone) (Jiang, 1991; Grunthal, et al., 1995).

One of the main difficulties of the PSHA method is the definition of the initial seismic source zone model. This method is suitable for areas with well-documented seismic history and sufficiently recorded seismic activity (Schmid, et al., 1995). However, in most cases the earthquake catalogues available are incomplete or too short to include all potential types of earthquakes that might occur. Hence, in order to construct the zone model it is therefore a primary necessity to make various decisions employing the use of geological and seismological data.

The accuracy of the predicted hazard at the site will depend upon the quality of the input information (i.e. the configuration of sources and their activity rates, the form and parameters of the attenuation relationship and the treatment of local effects). Small differences in the model can have quite large effects on the hazard (Veneziano and Van Dick, 1985, in Margottini, 1992). It can be concluded, therefore, that the features of the input parameters are more critical than the methodology of the calculation of the seismic hazard.

Sobaih, et al. (1994) used PSHA to estimate the ground motion hazard in Syria. To achieve their aim the research was divided into four main steps: spatial occurrence modelling, attenuation modelling, magnitude recurrence modelling and temporal occurrence modelling. The approach used had the capability of integrating effects of various seismic sources and providing quantitative evaluation of potential seismic hazard at the region under consideration. A comparison of the results of this approach to the ones obtained from other studies involving Historical Seismicity and Extreme value analysis-based hazard, showed a general agreement in the identification of active and non active seismicity zones.

Musson (1998) states that seismic hazard calculations for areas with low seismicity like the United Kingdom are generally based on PSHA. Ove Arup (1993) were the first to attempt to establish seismic hazard in the UK through a PSHA method.

Neophytou (1987) also used the PSHA method to model the magnitude recurrence (Gutenberg-Richter linear relation of frequency-magnitude) and temporal occurrence of earthquakes (Poisson model) for Cyprus.

Jiang (1991) however, opposes this method and argues that the level of subjectivity and personal decision that goes into constructing the zone model suggests that the PSHA is not perfect. In particular, the three assumptions, of homogeneity of the spatial distribution, stationarity of the temporal distribution and uniformity of the strength distribution, employed in this method, contradict the widely recognised non-homogeneity, non-stationarity and non-uniformity of these parameters (Jiang, 1991).

Jiang (1991), explains that, due to the utilisation of the homogeneous Poisson process, the seismic activity level does not change with time. The fact that a single "b" value (see the magnitude-intensity equation given in Figure 2.3) is used in a specific seismic zone implies that all the seismic sources in that zone have the same annual average occurrence rate (Jiang, 1991). Additionally, the seismic activity levels of all the seismic sources (either area or line source) in the same seismic zone are considered independent to each other. Finally, the earthquake activity of every magnitude is average. Jiang (1991), concludes that the end result of these assumptions is a possible underestimation of the real likelihood of risk of large-magnitude earthquakes.

To overcome these limitations Jiang (1991) suggests that it is important to improve the homogenous distributions of the seismic activity, in accordance with the recognition of its non-uniform characteristics. Jiang (1991) introduces a new version of PSH, a non-uniform method, suggested by some Chinese seismogeologists. The main objective of this method, is the determination of the temporal and spatial non-uniform distributions of the seismic activity (i.e. of the earthquake occurrence) (Jiang, 1991).

This form of seismic hazard analysis (i.e. PSHA) in whichever format (i.e. uniform or non-uniform) involves much more effort than the analysis required in the methodologies described before (i.e. observational, deterministic, statistical). Conversely, the fact that this analysis can cope with large amounts of data increases the capacity of the method.

PSHA methods used by reinsurance companies.

The Swiss Reinsurance Company (Schmid, et al., 1995) has suggested an alternative approach to the uniform PSHA method. Swiss Re. reinsures for earthquake risk on a world-wide basis, in an attempt to overcome the regional accumulation of losses and establish an equitable balance between premium income and losses.

Schmid, et al. (1995) argue that the available hazard assessment approach (uniform PSHA), although adequate for areas with extensive and accurate earthquake historical catalogues, is not suitable for a world-wide application. The reason for this is the extreme effort involved with the definition of the seismogenic zones as well as the lack of a complete mapping of the faults. They also suggest that the most recent seismicity analyses and maps are characterised by great differences in terms of databases and methods used as well as the transparency and quality of the results obtained. This reflects clearly that the application of this method in a world-wide extent is difficult. Furthermore, Schmid et al. (1995) state that the results of such studies (i.e. the current state-of-the-art in available regional seismicity analyses and maps) are frequently difficult to transform into risk models suitable for the insurance industry.

The method which was developed and is applied by Swiss Re. does not use individually defined seismic zones. The method is based on the assumption that each point in a global ½° grid of co-ordinates represents a possible earthquake source. The corresponding seismogenic parameters are not determined for individually defined seismic zones, instead they are allocated to each of these points (see Figure 2.4 on the following page).

The Swiss Re. seismicity model assumes that the frequency of occurrence of past events is representative for the future. Thus for an appropriate representation of the earthquake activity it is considered sufficient to estimate the occurrence frequency of past events. In order to estimate the earthquake activity of the point sources the historical activity (i.e. past earthquakes) is distributed over the grid points (i.e. the positions of the past events are spread out). The earthquake occurrence frequency can therefore be estimated statistically.

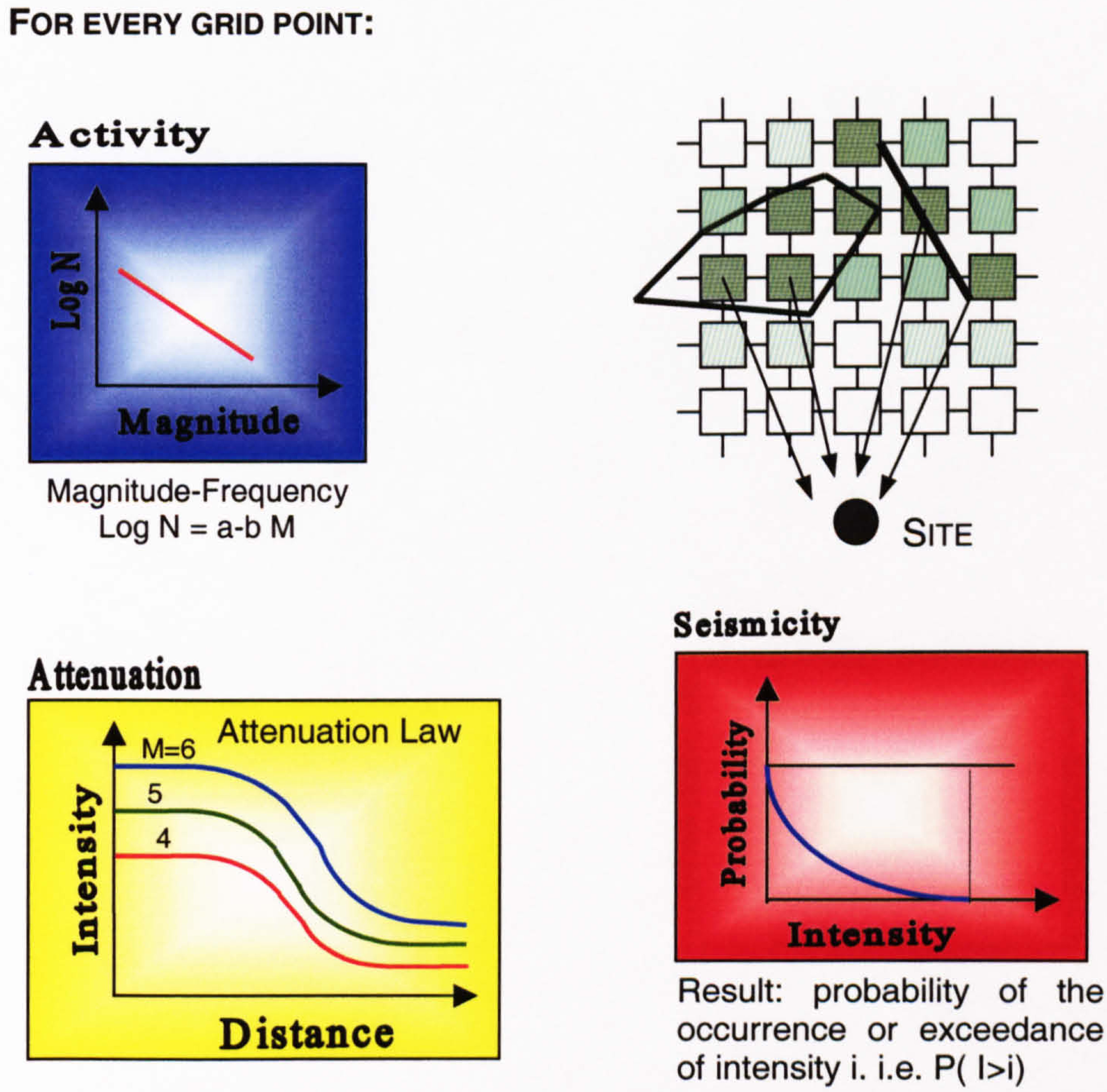


Figure 2.4. A schematic illustration of the Swiss Re's approach for seismicity assessment, allocating activity to grid points (Schmid, et al., 1995)

The following typical seismicity parameters characterise each individual point source.

1. Magnitude-Frequency relationship
   (i.e. the a and b values of the Gutenberg-Richter relationship)
2. Maximum Possible magnitude (i.e. M_S)
3. Focal depth distribution
4. Attenuation parameters.

These parameters can then be used for the calculation of the seismic hazard for each point source and ultimately for the entire area. The point sources allow calculations to be made in the same manner as with common seismic zones (Figure 2.4) or a more detailed resolution can be applied through interpolation between grid points.

The grid method proposed by Swiss Re. uses a relatively large grid width (55 km in N-S direction and 55 km or less in E-W direction). This could be a potential problem since the local seismicity profile of certain areas could be reflected insufficiently. However, this problem is relatively insignificant when the area under consideration is the whole world (the case examined by Swiss Re). This can be justified since other factors important in the determination of the risk such as the local subsoil, construction quality and geographical distribution of the insured values are not always available in great detail for this kind of geographical resolution requirements (Schmid, et al., 1995). On the other hand the coherent and transparent characteristics of this method counterbalance this weakness.

Based on Schmid, et al. (1995) this method enables the seismic hazard to be presented in a clear, adequate, and accurate way, which is ideally suited for computer aided risk analyses.

Since the current research involves computer aided earthquake risk analyses of the island of Cyprus it will be attempt to utilise a PSHA approach which has elements from many of the above methods to reflect the information available in a medium seismicity region.

PSHA and Seismic Hazard Maps

The PSHA method was initially developed particularly for individual sites, but it can be uniformly applied for a grid of points to obtain a regional seismic map with a certain probability level. In that case the values are contoured to illustrate the spatial variation of the hazard. The technique can be adjusted accordingly for any area size.

Seismic Hazard Maps have been considered as an essential step towards setting seismic zone maps for building codes and an important tool for the selection of design values in large and complex structural projects. Furthermore, seismic zone maps are also useful for insurance companies when they attempt to estimate the appropriate premiums for earthquake insurance.

At the end of the ERA, as part of the assessment of the RMS the seismic zonation map of Cyprus will be examined.

TIME DEPENDENT SEISMIC HAZARD

Further disadvantage of PSHA is the fact that it is based upon a principle known as stationarity. This principle states that the seismic hazard of an area is constant in time. This assumption is not always valid. For example an area, which has recently suffered a large earthquake, has been relieved of its seismic energy. Normally, it would require a certain period of time to pass, before enough energy accumulates in the same region to generate large earthquakes. Furthermore, there are areas where a big earthquake appears to be due or even overdue. According to Musson (1998) in an attempt to overcome these limitations various modifications were implemented to the PSHA, which introduce parameters describing average inter-event times and time since last event. The enhancement of the PSHA with these modifications resulted in Time Dependent Seismic Hazard method.

However, the occurrence of large earthquakes like the 1994, Shitokan (NE of Japan) event, proved the original assumption used in the PSHA to be fairly true. Large earthquakes occurred in areas, which suffered from large events in the near past, and one might have thought that not enough time had elapsed for sufficient seismic energy to accumulate. Furthermore, areas that one would expect have gathered enough seismic energy requiring release, remained tranquil. Consequently, the time dependent method can only be used in large areas where the time dependency is well understood, as for example in the case of the movements of the Arabian and Anatolian plates.

2.3.3.2 CONCLUSIONS

The various methods available for the estimation of the seismic hazard have been presented and their advantages and disadvantages have been analysed.

The Probabilistic approach is a convenient tool to evaluate uncertainties in the evaluation of seismic hazard assessment.

Taking into consideration the particular case of Cyprus and particularly the available data it was decided that for the assessment of the Seismic Hazard a modified version, to accommodate the non-uniformity of the spatial distribution of the earthquake events, of the Probabilistic approach would be followed.

2.3.4 OTHER ASPECTS OF RISK ASSESSMENT

Earthquake Risk is dependent upon the occupancy of the region under consideration and it is proportional to the number of human lives and the worth of goods lost during a certain period of time. Therefore, the distribution of the building stock over a region and the value of the elements at risk are crucial for the assessment of Earthquake Risk.

If the density of the building stock in a given area and the seismic hazard of that area are low, then the financial loss expected as the result of an earthquake is negligible.

However, if the opposite occurs then the human, structural and financial losses could be very high.

For example the urbanisation of seismic areas in the island of Cyprus (i.e. Paphos, Limassol, Larnaca), is accelerating. If the current urbanisation continues at the same rate and a period of intense seismic activity begins, larger financial and structural losses should be expected.

Furthermore, the risk from landslides and tsunamis are never zero. The factors that affect these risks are the location of the buildings and lifelines relative to the source, and the maximum severity of each disaster agent. The risks from the above mentioned disaster agents are at their highest in the following locations:

a) in or adjacent to seismogenic zones capable of generating damaging earthquakes and possible devastating tsunamis,

b) on unstable slopes susceptible to landslides triggered by seismological sources or even by meteorological sources (i.e. landslides due to high precipitation),

c) along coasts where tsunami flood waves can strike or severe liquefaction phenomena can occur.

The in depth examination of the tectonic setting of an area as well as the detailed studies of the local geological and topographical conditions are essential when building new structures, particularly ones of great importance (hospitals, airports, dams etc.).

In this study, the earthquake risk, fatalities and injuries are estimated based only on direct structural damage due to ground shaking. The possible risks due to landslides and tsunamis are not included due to lack of data. However, in the future these risks should be examined in detail.

All the parameters involved in the estimation of seismic risk can be given geographical co-ordinates and displayed and analysed in the form of maps. A Geographical Information System (GIS) is a computer system able to efficiently assemble, store, manipulate, and display geographically referenced information (data identified according to their location).

Various studies (see Section 2.4 - Appendix A) have already used GIS as part of the actual risk assessment. By superimposing various maps of different parameters (i.e. hazard, population distribution, building distribution, geology etc.) it is possible to extract specific information related to the risk. However, in this research the GIS will be used only for the visual presentation of the results. Some general information relating to the GIS is given in Section 2 of Appendix A.

2.4 RISK MANAGEMENT

Events such as earthquakes and the resulting landslides and tsunamis are inevitable. However, some of the disasters triggered by them are not. According to Hays (1994) the reduction of community earthquake vulnerability is a long-term process, which involves the creation of a basis for changing the way the community assesses and evaluates its hazard, built, and policy environments.

Every community can reduce its vulnerability by taking the appropriate actions that can either prevent or minimise the physical and social demands of earthquakes and increase the community's ability to cope with them. A number of actions that can be considered part of a community's options for risk management, suggested by Hays (1994), are presented in Table 2.1.

Once the ERA for Cyprus is completed it will be used in an attempt to assess and compare various RMS.

Table 2.1. Options of Risk Management by Hays (1994)

Prevention	Actions that prevent the occurrence of physical and/or social demands or actions that prevent loss of community capability
Mitigation	Actions that reduce the physical and/or social demands or actions that protect community capability
Preparedness	Actions that anticipate and reduce the physical and/or social demands or actions that enhance and protect community capability
Prediction and Warning	Actions to predict and warn the populace about the occurrence and consequences (where, how big, when and probability) of physical and/or social demands or actions to protect community capability from eminent events.
Intervention	Actions taken while the physical effects of the natural hazard are still developing in order to lessen the expected physical and/or social demands or actions that lessen the expected impacts on community capability.
Emergency response	Actions that define the expected physical and/or social demands or actions that manage and reallocate community resources to protect community capability.
Recovery	Actions that stabilise the physical and/or social demands for actions that restore and improve community capability.

2.5 PARAMETERS AFFECTING THE EARTHQUAKE RISK IN THE CYPRUS REGION

2.5.1 INTRODUCTION

This section will introduce and explain the parameters affecting the earthquake risk in the region of Cyprus. The tectonic setting and general seismicity of the region will be addressed including the historical seismicity, frequency of earthquake occurrence, seismic zones and the Cyprus seismic network. A study of the geology of Cyprus including its creation and its surface geology will be followed by an introduction to the attenuation curves and the building vulnerability.

2.5.2 TECTONIC SETTING AND SEISMICITY OF CYPRUS

Cyprus lies within the second largest earthquake zone of the earth (Figure 2.5) but in a relatively less active sector than Greece and Turkey. This zone stretches from the Atlantic Ocean across the Mediterranean Basin, through Greece, Turkey, Iran, and India and goes as far as the Pacific Ocean. The energy released by the earthquakes in this zone represents 15% of the global seismic energy.

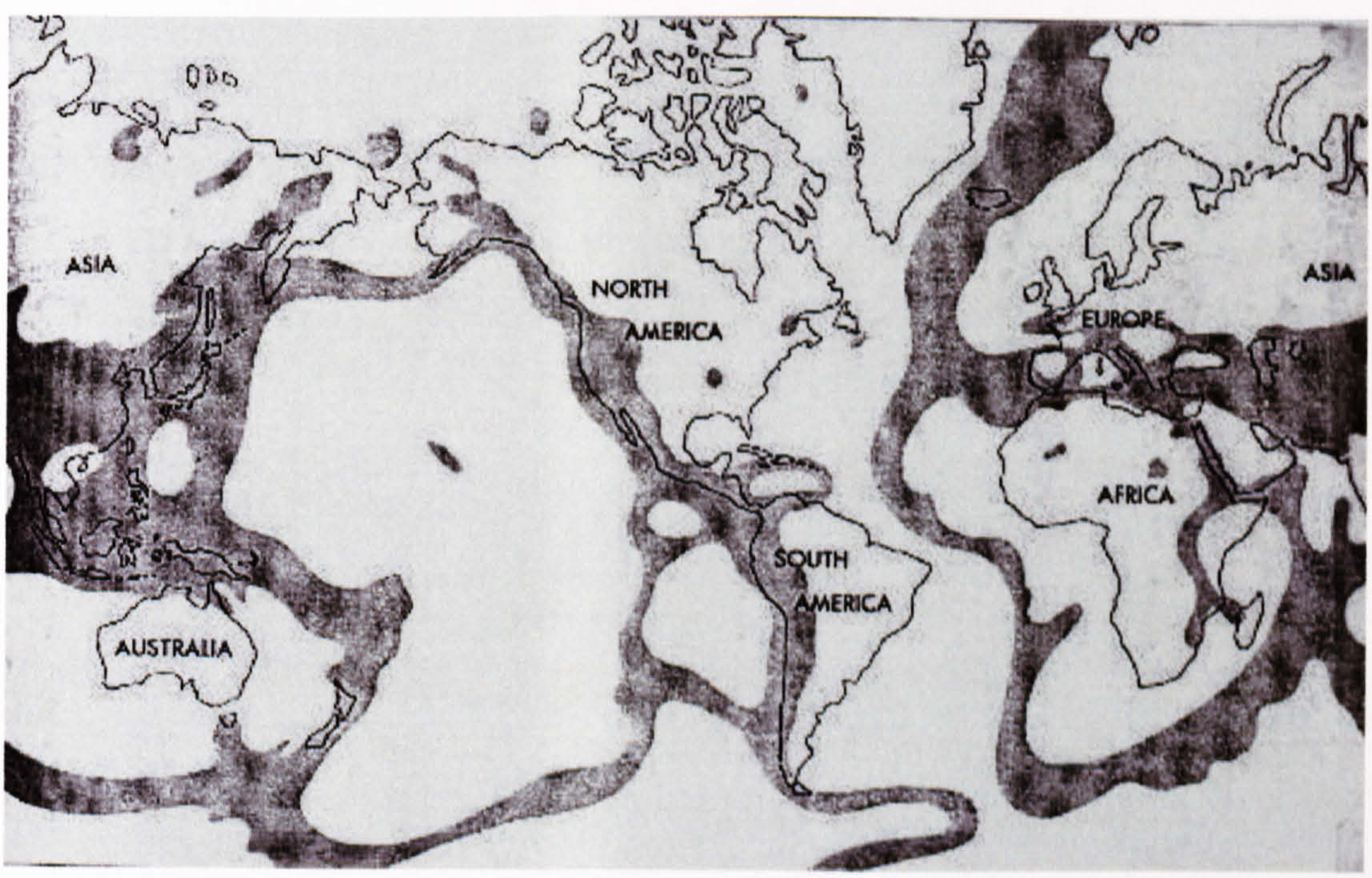


Figure 2.5. Earthquake zones of the Pacific Ocean, the Mediterranean Basin and Asia release 95% of the world's seismic energy (Levy and Salvatori, 1995)

The earth's crust is divided in 12 major plates. In addition to these, there are some smaller plates like the Aegean plate of the Hellenic Arc. The island of Cyprus has its own arc appropriately named the Cyprian Arc.

The Cyprian Arc is the point of contact of the African plate with the Eurasian plate (Figure A-1 – Appendix A). The African plate, which is moving towards the north, pressurises the Eurasian plate. This causes the build-up of forces. When the build-up of stresses reaches a maximum limit, a crack is created on the crust of the earth in that specific area. The result is the movement of the tectonic plates, until a balance is reached again.

Ambraseys and Adams (1992) stated that:

"Cyprus lies on the southern part of a diffuse boundary between the African and the Eurasian plates in a general zone of shortening which extends in an arcuate shape between the Gulf of Antalia in the west and the Gulf of Iskenderum in the east. In the west the Cyprian Arc meets the eastern end of the Hellenic Arc under southern Turkey in an area with subcrustal and intermediate depth earthquakes (h>40Km and h>70Km respectively). In the east it joints the East Anatolian fault zone which extends north-westwards through Turkey from the continuation of the Dead Sea rift system up the Syrian coast" (Figure 2.6).

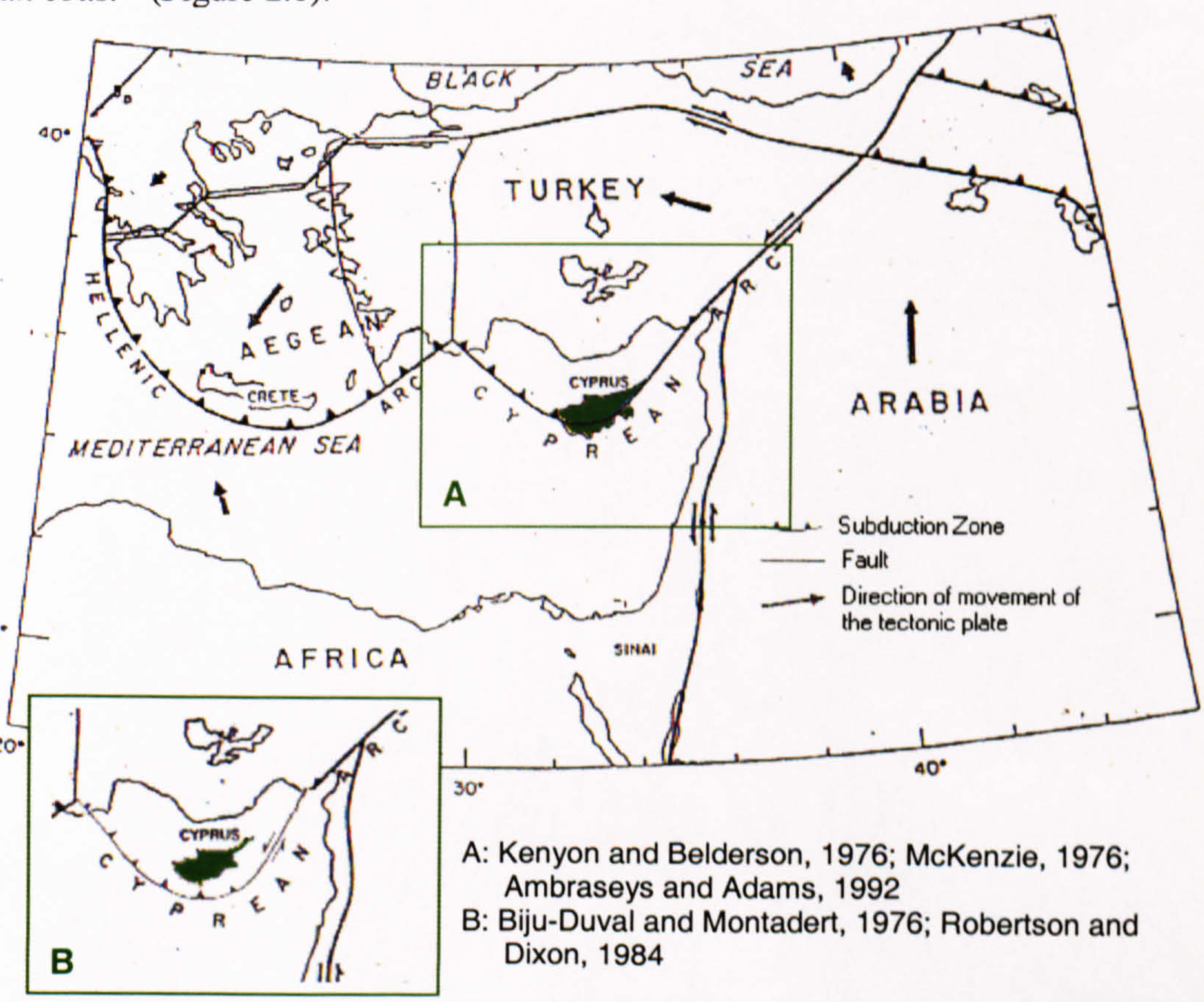


Figure 2.6. Arrangement of the tectonic plates in the East Mediterranean. The Cyprian Arc is shown as a plate boundary (after Ambraseys and Adams, 1992; after Grambis, 1997)

Opinion differs as to the exact position of the Cyprian Arc, with some scientists positioning it along the southern end of the Troodos Massif (Figure 2.6) (Kenyon and Belderson, 1976; McKenzie, 1976; Ambraseys and Adams, 1992).

However, more realistic explanations show the Cyprian Arc curving offshore around the southern coast of the island (Figure 2.6) (Biju-Duval and Montadert, 1976; Robertson and Dixon, 1984).

The structure of the Cyprian Arc is complex and the availability of information concerning it, is very poor. There is an agreement of opinions regarding the general shape of this arc, but there is not a clear view on whether it is a plate boundary (McKenzie, 1972, in Ambraseys and Adams, 1992) (Figure 2.6), or a broad zone of thrusting (Figure 2.7), (Rostein and Kafka, 1982, in Ambraseys and Adams, 1992).

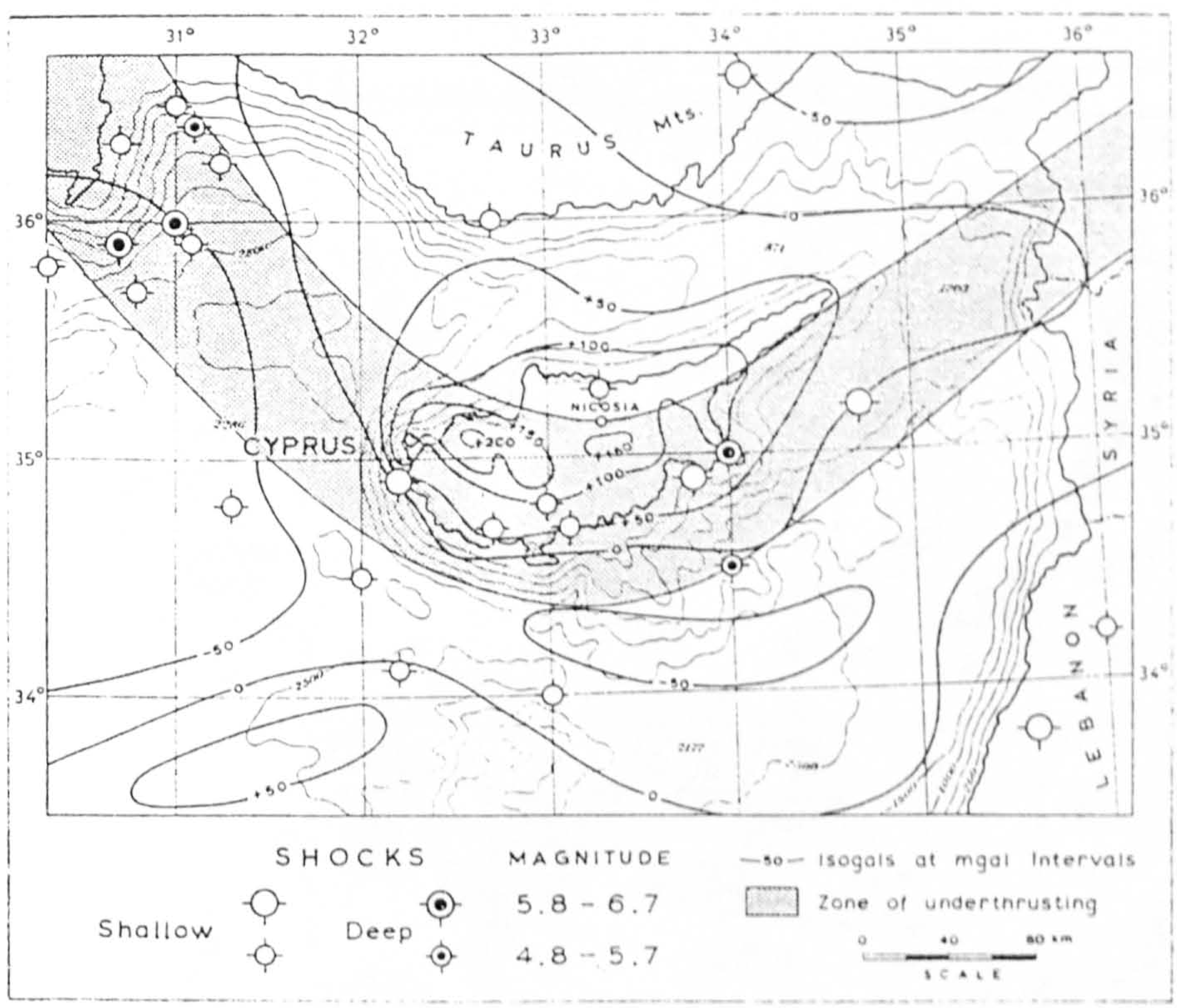


Figure 2.7. The Cyprian Arc illustrated as a broad zone of thrusting (Galanopoulos and Delibasis, 1965)

There is evidence (earthquakes at subcrustal depths) that subduction is occurring in the Antalia Basin, the north-west part of the arc, but for the rest of the arc there is no evidence to suggest the same. Therefore the extension of this subduction zone towards Cyprus can only be speculative (Ambraseys and Adams, 1992).

Most scientists believe that this Cyprian Arc is responsible for most of the earthquakes occurring in the area of Cyprus. Pilakoutas, et al. (1995) stated that the main current seismic activity in the area of the island of Cyprus appears to originate from the Cyprian Arc. Figure 2.8, shows all the events regardless of magnitude from 1915-1992 held in the ISC (International Seismological Centre) files for the region of interest, and it can be seen that the main seismic activity is concentrated on the west and south part of the island, as well as in an arcuate formation (Cyprian Arc) in the sea area to the south-west. The vast majority of the seismic activity from 1919 until 1995 occurred south of the 35° parallel. On the north-west of the island there is relatively low seismic activity compared to the Antalia Basin further to the north, where the seismic activity is much more intense. A similar low seismic activity to the one at the north-west of the island, but in a way less intense can be observed on the north-east of Cyprus towards the Gulf of Iskenderum (Figure 2.8).

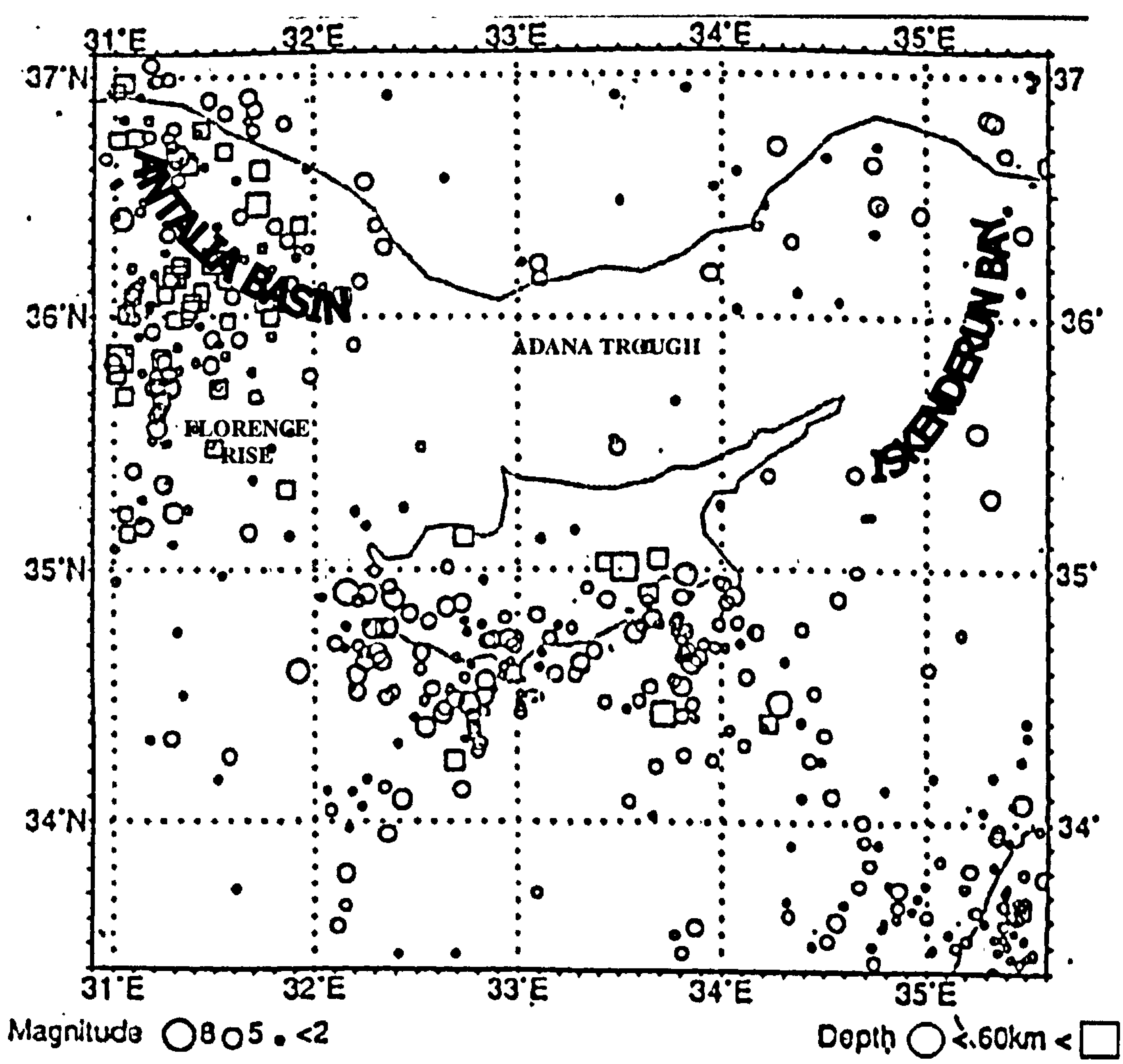


Figure 2.8. All events regardless of magnitude held in the ISC files for the region of interest from 1915-1992 (after Ambraseys and Adams, 1992)

2.5.2.1 HISTORICAL SEISMICITY OF CYPRUS

The island of Cyprus has been hit by earthquakes many times and historically the towns were affected by strong earthquakes many times in the past. In 76 AD Salamina, Larnaca and Paphos were destroyed completely by an earthquake, which is the strongest to have stricken the island to date. Salamina and Paphos were destroyed for a second time in 332 AD and 342 AD respectively. Some evidence of the damage caused to the ancient Hellenic cities by several earthquakes can be found today in their ruins.

In the past, earthquakes were described by historians, travellers and monks, who only referred to the strong and destructive earthquakes without mentioning any other less destructive events. The historical record prior to 1896 shows many weaknesses and voids. For instance for the periods 80 - 320 AD, 400 - 1140 AD and 1600 - 1718 AD there are no recorded observations. This was due to the unstable political conditions which were dominating Cyprus during those periods and the scarcity of population. The Arabic raids in the middle ages and then the Ottoman occupation of Cyprus contributed to the decrease, or lack of, information about earthquakes.

It should also be appreciated that existing historical records may have been exaggerated by the historians and the chronographers who described them.

INSTRUMENTAL RECORDINGS OF THE LAST CENTURY

In 1896 the first international seismological stations were established. Since then there has been a significant increase in the number of reported earthquakes. Characteristically, between 1896 and 1980, 755 earthquakes (with magnitudes greater than 4.0 in the Richter scale) were reported in the area of Cyprus (Solomis, 1995).

During the last fifty years the data concerning the earthquakes that occur in the area of Cyprus has become more precise and accurate due to the existence of a network of seismological stations in the countries of Eastern Mediterranean. This has made it possible for more than 60 earthquakes of intensity 6 and above on the Mercalli scale, with epicentres in a distance less than 50 km from the coasts of Cyprus, to be reported (Protopapas, 1987). Since the establishment of the seismological stations in the neighbouring countries various non-damaging events with $M_S > 5.0$ have been reported (Table 2.2) including a total of 16 damaging earthquakes (Table 2.3). The better quality in the earthquake data of recent years can also be partially attributed to the establishment of the seismological station of Cyprus, in 1984 (section 2.5.2.4).

The most destructive earthquakes of the 20th century were the ones that occurred in 1941, 1953 and 1995 with corresponding magnitudes of 5.9, 6.1 and 5.7. They lasted from 15 to 20 seconds causing many fatalities and extensive damages.

Table 2.2. Events with M_S>5.0 recorded in the area of Cyprus during the last century and did not cause any damage

No*	Date	Epicentre	M_S	Comments
1	13 /1/ 1894	35.60-34.70	5.5	Felt strongly in Kyrenia and Nicosia
6	29 /9/ 1918	35.10-34.80	6.3	Felt throughout the island.
7	19./8/ 1919	35.20-34.70	5.4	No macroseismic information from Cyprus.
8	20 /4/ 1921	34.60-34.00	5.3	Rather strongly felt in the district of Larnaca.
12	16 /8/ 1940	36.19-31.40	5.3	The shock was felt in Limassol.
14	9 /12/ 1947	36.46-34.66	5.4	Felt throughout Cyprus.
15	1 /2/ 1953	33.50-32.00	5.5	The shock was felt in Limassol.
20	12 /1/ 1976	34.44-32.63	5.0	Felt strongly in Limassol
21	28 /5/ 1979	36.46-31.72	5.3	Felt in Limassol, Paphos and Nicosia.
★	23 /4/ 1999	35.81-31.92	5.0	Felt in the district of Paphos.

**No - refers to Figure 2.10*

Table 2.3. The damaging earthquakes of Cyprus from 1896 to 1997 (No - refers to Figure 2.10)

No	Date	Epicentre	M_S	Damage description
2	29 /6/ 1896	34.30-33.00	6.5	Felt strongly along the south coast of the island. It lasted about 15 seconds. The shock caused cracks in the ground, liquefaction of deposits, rockfalls from cliffs, collapses of houses. The sea became agitated. Episcopi and Acrotiri were particularly affected. Many aftershocks followed for a four month period.
3	3 /7/ 1896	34.30-33.00	5.2	Strong aftershock of the above earthquake causing additional damage to houses and buildings.
4	5 /1/ 1900	34.00-34.50	5.7	Strongly felt throughout Cyprus, lasted for about 15 seconds. Minor damage in the Mesaoria plain.
5	23 /2/ 1906	34.30-33.50	5.3	Minor damage in Limassol and Kolossi. The earthquake was felt all over the island.
9	18 /2/ 1924	34.80-34.30	6.0	The shock was very strongly felt in south-east Cyprus. Minor damage in Famagusta.
10	13 /12/ 1927	34.80-33.00	5.0	Lasted about 10 seconds. Minor damage to schools and other buildings in the town of Limassol and to some villages in the north of the Limassol district. (Kilani, Pera-pedi, Monagri)
11	9 /5/ 1930	34.64-32.19	5.5	Damages in the town of Paphos and to the surrounding area. Landslides and settlement of the ground, schools, churches and many houses were damaged.
	26 /6/ 1937	34.88-32.80	4.9	Damages in the south-west part of the island. (Pachna, Omodos, Arsos, Platres, Salamiou, Agios Nicolaos, Kilinia, Agios Ioannis)
13	20 /1/ 1941	35.17-33.65	5.9	Felt througout Cyprus. Serious damage in the Famagusta district. In Paralimni 24 people were injured and many buildings collapsed. The districts of Nicosia, Larnaca and Kyrenia suffered some minor damage.
16 17	10 /9/ 1953 10 /9/ 1953	34.72-32.24 34.80-32.78	6.0 6.1	Destructive double earthquake with victims and extensive damages in the town and district of Paphos. 40 people died, 150 were injured. A large number of houses collapsed making 4000 people homeless. A number of buildings and churches were also damaged. Historical monuments suffered severe damage. The earthquake also caused 158 landslides, ground cracking, rockfalls, and settlements. Liquefaction occurred in the Limassol district. A small tsunami hit the coast of Paphos. Aftershocks continued for over a month, some causing additional damage.
18	16 /3/ 1956	33.60-35.50	5.1	Two shocks 10 minutes apart were strongly felt in Limassol. Light damage was caused.
19	15 / 9 / 1961	34.91-33.83	5.7	Felt throughout Cyprus. Minor damage in the town of Larnaca and the surrounding area. Two people were injured.
	28 /3/ 1984	34.75-33.58	4.5	Particularly felt in the town and district of Larnaca. Minor damages.
★	23 /2/ 1995	35.10-32.30	5.7	Destructive earthquake in the area of Paphos with 2 fatalities. A large number of houses collapsed in the villages of Pano Arodhes and Miliou. Damages were also reported in the villages of Peristerona, Steni, Gialia, Argaka, Pomos, Pyrgos, Lefka, Neo Chorio, Latsi and Poli Chrysochous. Fishes were found on the rocks of the Akamas beach which suggests a small tsunami.
★	9 /10/ 1996	34.49-32.21	6.5	Very destructive earthquake in the south-east part of Cyprus. Two people died due to secondary causes (i.e. heart attacks) and 85 were injured. Serious damage was reported in Paphos, Limassol, Nicosia and Larnaca. A large number of strong aftershocks with magnitudes from 4.9 to 5.1 followed for the next couple of months, some of which were felt as far as Nicosia.
☆	13 /1/ 1997	34.31-32.33	5.8	Felt throughout Cyprus causing little damage in the districts of Paphos and Limassol.

2.5.2.2 FREQUENCY OF EARTHQUAKES IN CYPRUS

Despite all the gaps and weaknesses of the historical data, Solomis (1995), concluded that from 1500 BC and until 1900 AD there were 30 destructive earthquakes of intensity 8 and above on the Mercalli scale, resulting in a statistical frequency of the order of 1 every 120 years.

On the other hand the German re-insurance company Munich Re, in their Universal Map of Natural Disasters, gives a probability of 20 % in 50 years for an earthquake with intensity 8 or more in the Mercalli scale (equivalent to about a magnitude 6 or more on the Richter scale) to occur in Cyprus. This means that by assuming a random distribution of earthquakes the return period for such an event is 224 years, almost twice as much predicted by Solomis.

By using the Ambraseys (1992) recurrence relationship (discussed later) this gives a return period of approximately 22 years, for an earthquake of magnitude 6 or more on the Richter scale.

A different source (Santamas, 1988), reports that since the beginning of this century, Cyprus was shaken close to 800 times by earthquakes of magnitudes ranging from 4.0 to 7.0 on the Richter scale. During this time the island has experienced 21 earthquakes in the range of 5.0 or greater which caused death to no less than 60 people and damages ranging in the millions. From information that has been collected in the past about the seismic activities in, or around the island, the conclusion has been drawn that there is a possibility of a potentially damaging earthquake occurring approximately every 12 years and a destructive earthquake every 25 years.

It is clear that different sources give different earthquake frequencies some varying quite considerably between themselves. This is based on the number of events examined, the source from which they were recovered and also in what type of time period they occur (period of intense seismic activity or period of seismic tranquillity).

When studying the historical facts and the seismic records of the last century it can be observed that periods of intense seismic activity are followed by long periods of seismic tranquillity and vice versa (Figure 2.9). Whilst the number of earthquakes reported with M_S>4.5 during the period of 1920-1929 was 11 the number decreased to 4 for the period 1930 to 1939 (Table 2.4). This fluctuation can be observed in other decades as well. Between 1960 and 1994 relative tranquillity was observed in the area of Cyprus, but seismic activity in the area of Cyprus has been increasing since 1995. The main earthquakes in the region of Cyprus during the period 1894-1999 are illustrated in Figure 2.10.

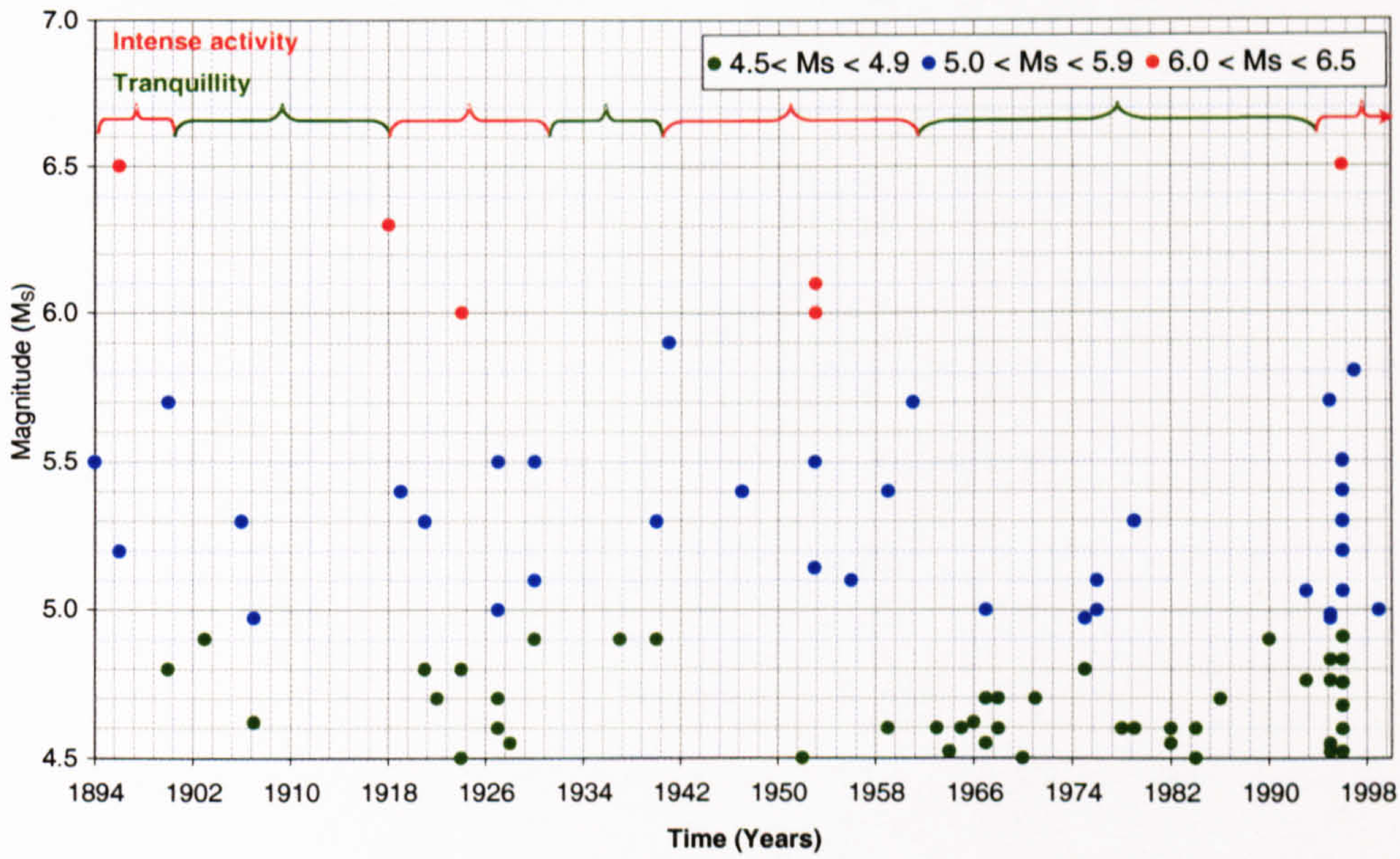
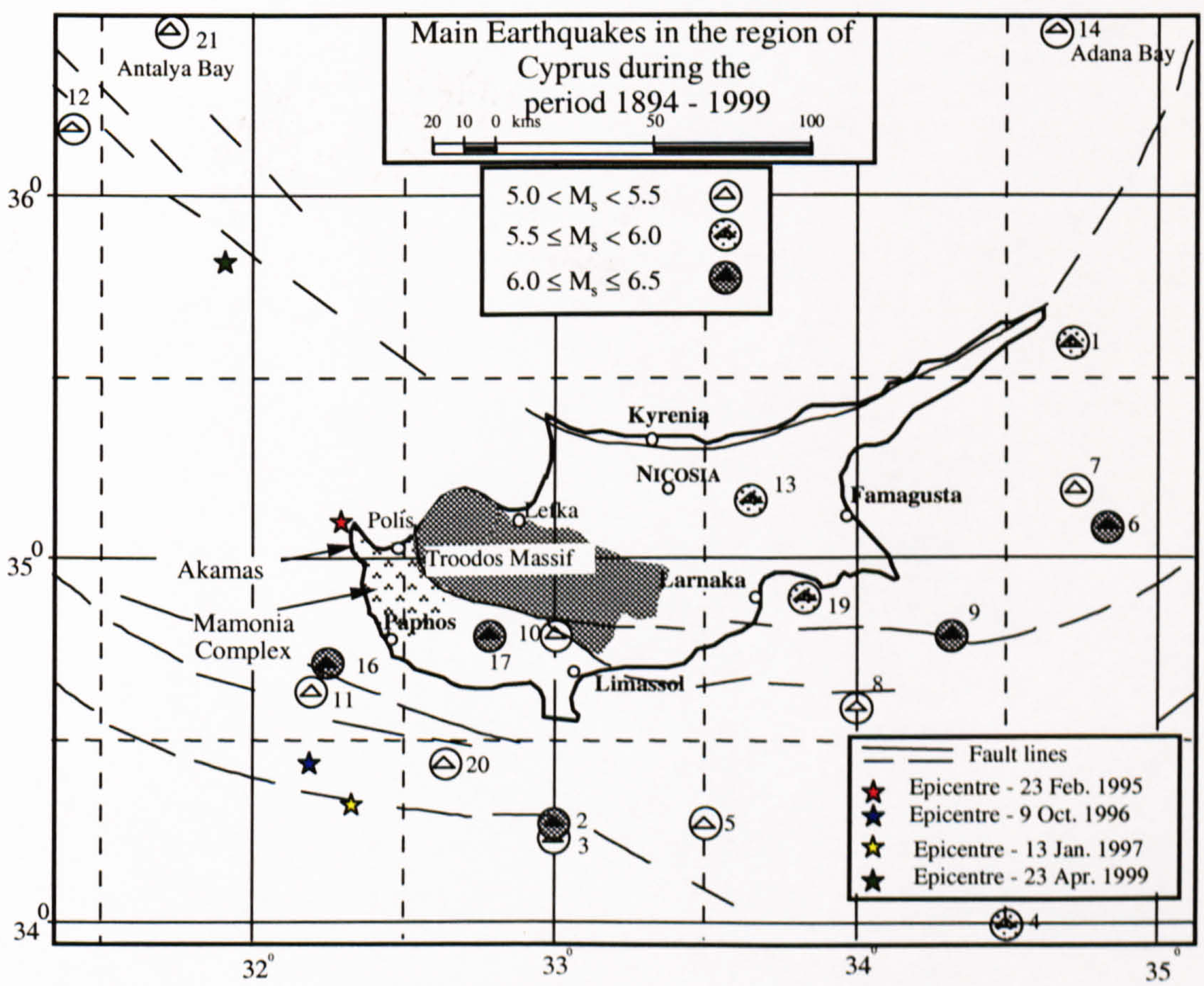


Figure 2.9. Earthquake events with M_S>4.5 in time



(For the numbering of the earthquakes see Table 2.2 and

Figure 2.10. The main macroseismic events (M_S>5.0) in the Cyprus Region during the last century

Table 2.4. Number of earthquakes with M_S >4.5 recorded between 1900 and 1997

Decade	Number of earthquake events with M_S>4.5
1900-1909	6
1910-1919	2
1920-1929	11
1930-1939	4
1940-1949	4
1950-1959	9
1960-1969	10
1970-1979	9
1980-1989	5
1990-1997	35

RECURRENCE RELATIONSHIP

For the purposes of this research it was assumed that the seismic activity in the region of Cyprus remains practically constant with time and that the rate of earthquake occurrence in the area under study, is defined by the Gutenberg – Richter relationship:

$$\log N = \mathrm{a} - \mathrm{b}M_S \quad \textbf{(2.3)}$$

where: N is the number of earthquakes with magnitude equal to or greater than the specified M
a is a parameter, depending on the region and time sample
b is a constant, seismic characteristic of a particular region
M is the surface-wave magnitude

There are various ways of expressing the seismicity of a region. Maps of epicentres, energy released or maximum intensity, give a qualitative expression of the seismicity. However, the ratio a/b, which expresses the maximum magnitude of the earthquake which has the greatest probability of being observed within a definite region and specified period of time, is the most reliable measure (Neophytou, 1987). This is mainly due to the fact that this measure allows the estimation of the maximum magnitude earthquakes which have the greatest probability of being observed in various time periods.

Ambraseys (1992), based on macroseismic and instrumental data, reappraised the last century's seismicity of Cyprus. He derived the following recurrence relationship:

$$\log N = 2.5 - 0.64M_S \quad \textbf{(2.4)}$$

where : N is the number of earthquakes per year in an area of six square degrees which will have a magnitude greater than M_S.
M_S is the specified magnitude.

Unfortunately, there are various factors which make this relationship not very applicable for PSHA.

1. The proximity of the island of Cyprus to complex tectonic zones and the "non-linearity" of the historical seismicity.
2. The fact that the formula was determined during a relatively quiescent century
3. The assumption of uniform distribution of events used to derive the formula which does not correlate with the known seismic hazard source (Cyprian Arc).

For the purposes of this research it was decided to attempt a reanalysis of the seismic data (see chapter 3) from 1894 up to the present time. In order to achieve this, it was essential to use the most complete catalogue. From the available data it was possible to prepare a catalogue which included all the events with M_S>2.5 from 1894 until April 1998 corresponding to the geographical area of 33°-37°N and 31°-35.5°E.

2.5.2.3 SEISMIC ZONES OF CYPRUS

A study of the seismicity of Cyprus based on the earthquakes that occurred in this area the last 2000 years allows us to make the following conclusions:

- The most earthquake stricken area of Cyprus is the south coast zone, which stretches from Paphos through Limassol to Larnaca and reaches Famagusta.
- The second seismic activity zone includes the Mesaoria plain, Karpasia and Kyrenia district.
- The area of the Troodos Mountains shows the smallest seismic activity from all the areas of the island.

The seismic hazard has a direct/immediate connection with the geology of the ground. Areas with hard rocks, like the ones of Troodos, have smaller seismic hazard and areas with loose dykes and liquid sediments a larger one. That is the reason why the Troodos area presents the lowest seismic hazard (Figure 2.11).

The south coast high seismicity zone is related to the Cyprian Arc (Section 2.5.1). The first attempt to divide the island of Cyprus into different seismic zones depending on the observed Modified Mercalli Intensities (MMI) of the occurred earthquakes was made in 1983 (Grambis, 1997). The input data used was significantly limited and the historical data were incomplete and inaccurate. Therefore, the resulting map (Figure 2.12) of the seismic zones of Cyprus was very general, separating the island into three zones based on the maximum observed seismic intensity which reached X (Section 3 - Appendix A) on the Medvedev-Sponheuer-Karnik (MSK) intensity scale.

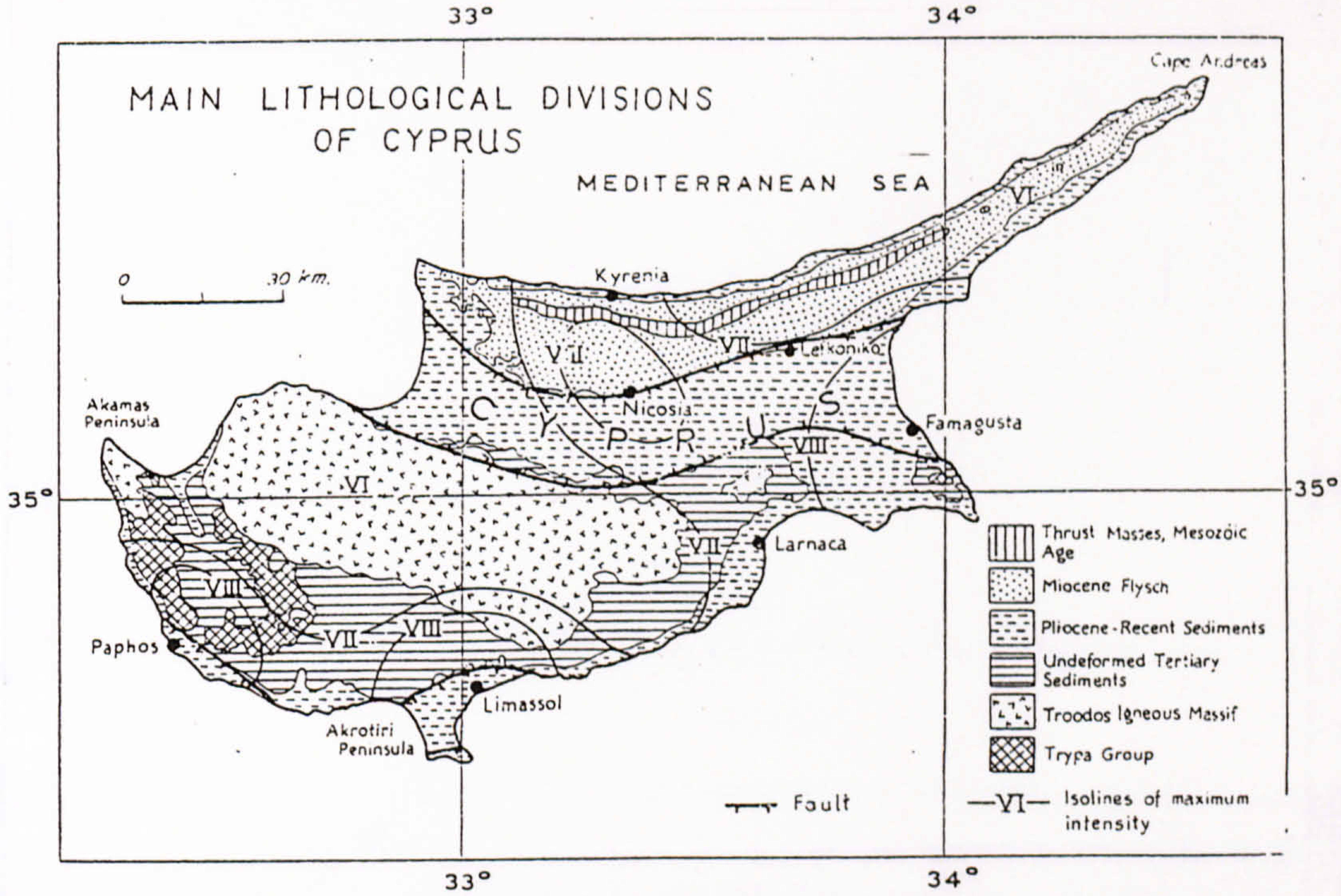


Figure 2.11. Main Lithological Divisions of Cyprus with a crude demonstration of the isoseismals of maximum intensity (Galanopoulos and Delibasis, 1965)

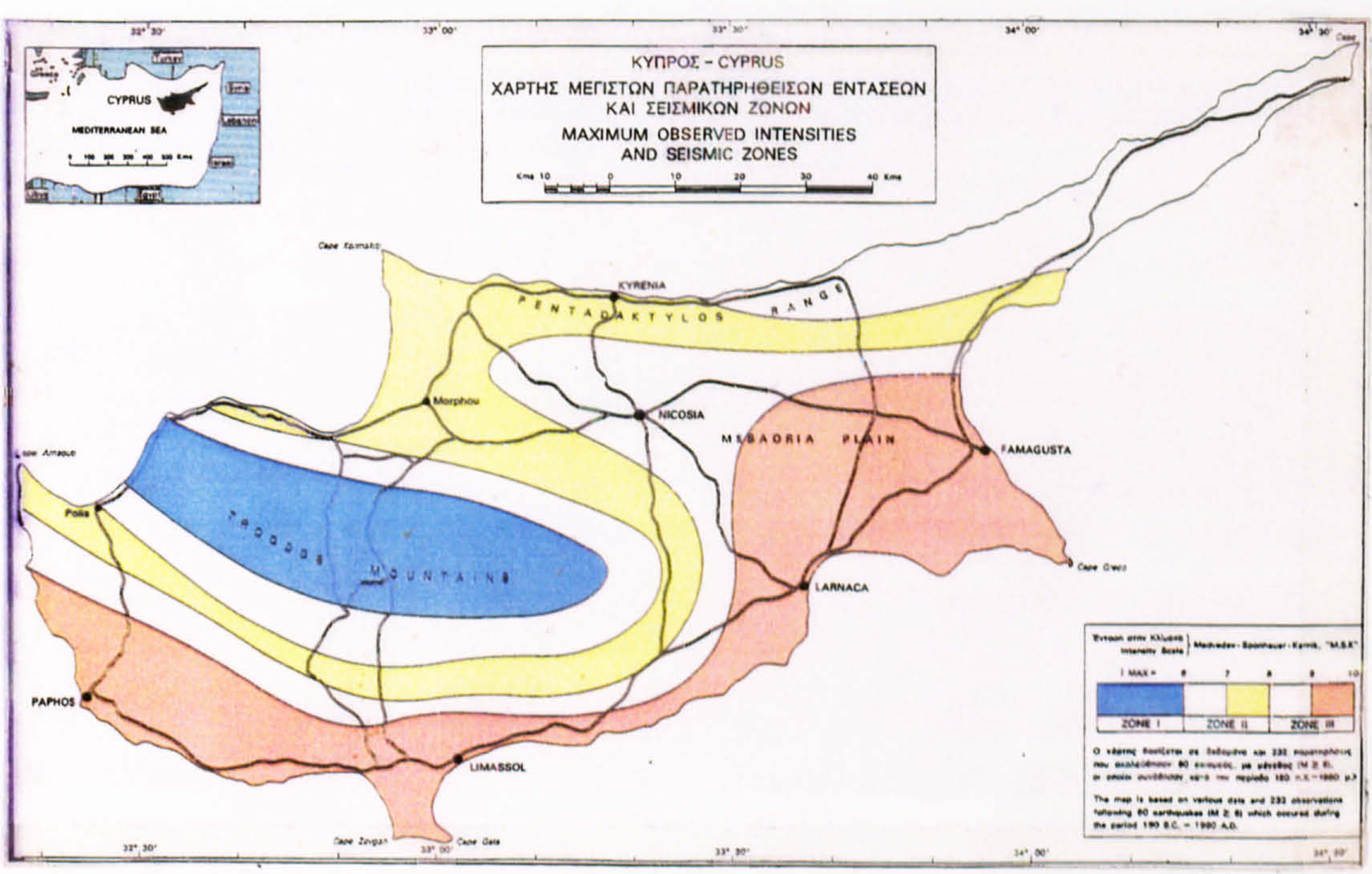


Figure 2.12. Maximum observed intensities and seismic zones map of the island of Cyprus prepared by the Geological Survey Department in 1983 (Grambis, 1997)

As it can be seen in (Figure 2.10), all the major earthquakes of magnitude greater than M_S 6.0 occurred close to the Cyprian Arc. During this century the majority of the earthquakes occurred offshore and the island incurred only relatively minor damage, the only exception being the 1953 (double) earthquake.

2.5.2.4 THE CYPRUS SEISMIC NETWORK, SITUATION AND PROCEDURES

The Seismological Section of the Geological Survey Department of the Ministry of Agriculture and Natural Resources of Cyprus studies the seismic activity in and around Cyprus.

The seismic data are obtained through the operation of a seismograph station network, which started in 1984 with the installation at Mathiatis (CSS-Central Seismograph Station) of one seismograph with a vertical component seismometer. In 1987 five additional seismographs were installed at the Mathiatis (CSS) receiving data from two sub-stations, one west of the island at Paphos Peyia (PPCY-Paphos Peyia Cyprus) and one east of the island at Ayia Napa (FAM-Famagusta) (Figure 2.13).

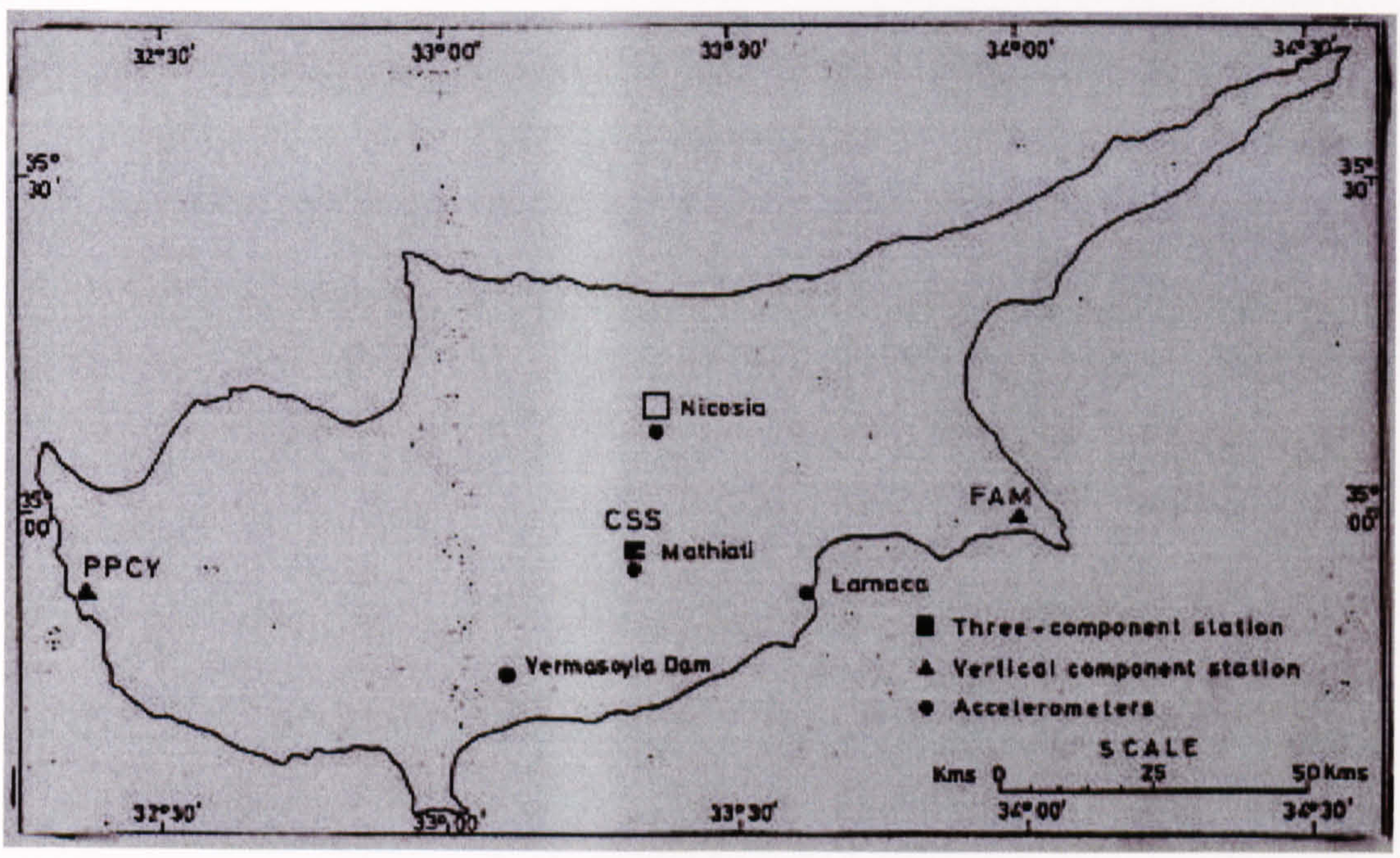


Figure 2.13. The Cyprus Seismic network (Solomis, 1996)

The Mathiatis Central Station is equipped with a three component system and the other two stations are equipped with vertical seismometers. Seismic data of the Mathiatis seismometers are analogically recorded. The seismic data of the sub-stations are transmitted to the Mathiatis Central Station by a combination of radio telemetry and hard wire telephone line. All data are analogically recorded on heat sensitive papers.

An array of 4 accelerometers operates throughout the country. These are strong motion accelerometers (SMA 1). The accelerometers are set to trigger at 10cm/sec² (the usual is 50cm/sec²). The accelerometers are situated one in Nicosia, one in Yermasoyia Dam, one in Larnaca and one in the Central Seismological Station at Mathiatis (CSS).

Between the opening of the seismological station of Cyprus and 1995, there were no recordings of earthquakes with magnitudes greater than 5.1 on the Richter scale. Only two events caused minor damage, in Larnaca (1984) and in Nicosia (1987).

During the last 10 years the reports show that every year there is an average of about 5 earthquakes, of intensities III to V on the Mercalli scale and magnitudes 3.5 to 4.0 on the Richter scale occurring in Cyprus. Smaller earthquakes with magnitudes 2 to 3 in the Richter scale are recorded in the order of at least 20 per month but nobody feels them.

A study of the seismic record of the last century made by the Geological Survey Department of Cyprus gave the following statistical results (Table 2.5).

Table 2.5. Return period of earthquakes in the area of Cyprus based on their magnitudes (Grambis, 1997)

Surface Magnitude (M_S)	Return period (years)	Number of earthquakes every 100 years
6.6-7.0	166	0.6
6.1-6.5	75	1.3
5.6-6.0	36	2.8
5.1-5.5	26	3.8
4.6-5.0	8	12.5

The improvement of the existing seismological network of Cyprus is essential and it can be achieved by:

(a) the establishment of two to three additional triaxial substations with three components, one vertical and two horizontal;

(b) the computerisation and automation of the recordings and analysis of the earthquake events;

(c) the telemetric connection of the stations with the offices of the geological survey department in Nicosia which will house all the recording systems; and

(d) the installation of additional accelerometers particularly in buildings of vital importance (i.e. hospitals, airports, dams etc).

This improvement will enable the rapid release of information of any felt earthquake events to the appropriate authorities and the public, which will help in reducing the spread of panic. Furthermore, it will provide the means for a fast and accurate analysis of the seismic data and a quick reporting of the results to the regional and global seismological centres, which is essential as far as the accurate determination of the parameters of the earthquake are concerned. Finally, the collection of reliable data for the seismicity of Cyprus, which can be used for a better determination of the seismic hazard, is expected to be achieved.

2.5.3 GEOLOGY

2.5.3.1 THE CREATION OF CYPRUS

The geological history of Cyprus began approximately 90 million years ago when a gigantic rupture of the earth's crust became the field of a huge undersea volcanic action and was followed by three main tectonic events:

(1) The genesis of the Troodos complex (Figure 2.14) over an oceanic subduction zone and, during the same period, the addition to it of sedimentary rock layers. The rock layers have varying ages of 200 million to 75 million years.

(2) A tectonic tranquillity started around 75 million years ago and stopped 10 million years ago. This period is characterised by the sedimentation of pelagic limestones and the gradual reduction of the depth of the sea.

(3) The joining of the Kyrenia range to the north side of the Troodos complex and the elevation of the island to its current position.

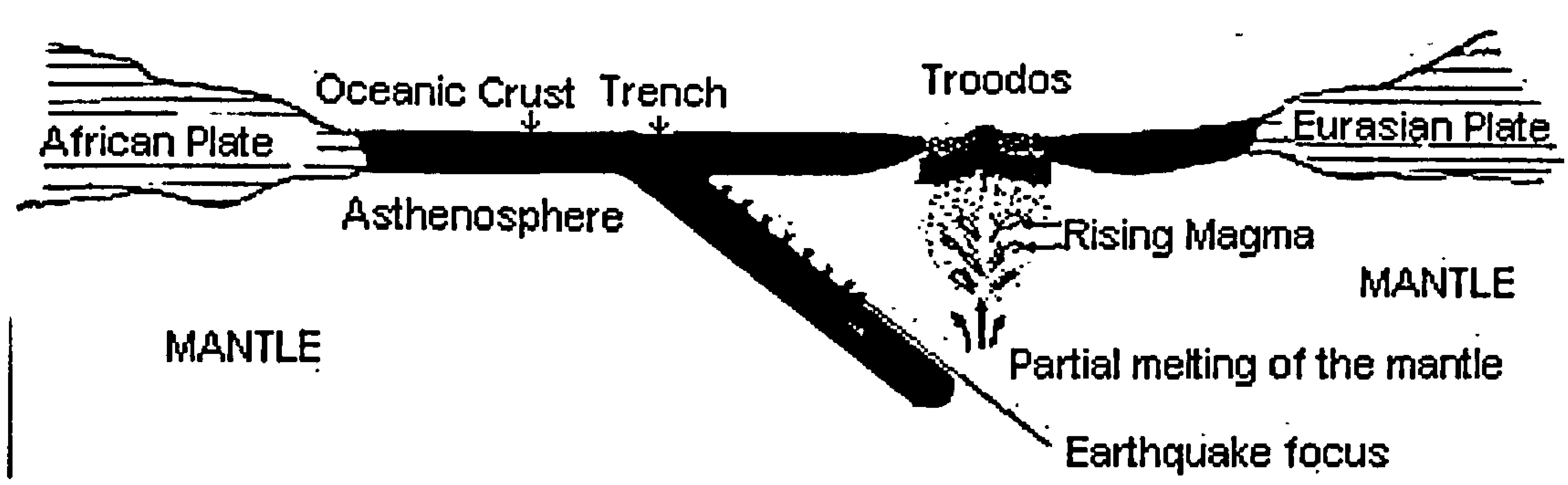


Figure 2.14. A schematic representation of the collision of the tectonic plates and the genesis of Troodos, 90 million years ago (after Xenophontos, 1997)

Cyprus is separated into three geotectonic zones, the Troodos range (and its continuation under the Mesaoria plain), the Mamonia zone and the Kyrenia range (Figure 2.15). In general there are two mountain ranges (Troodos and Kyrenia) that dominate the topography of Cyprus, separated by a central plain (Mesaoria).

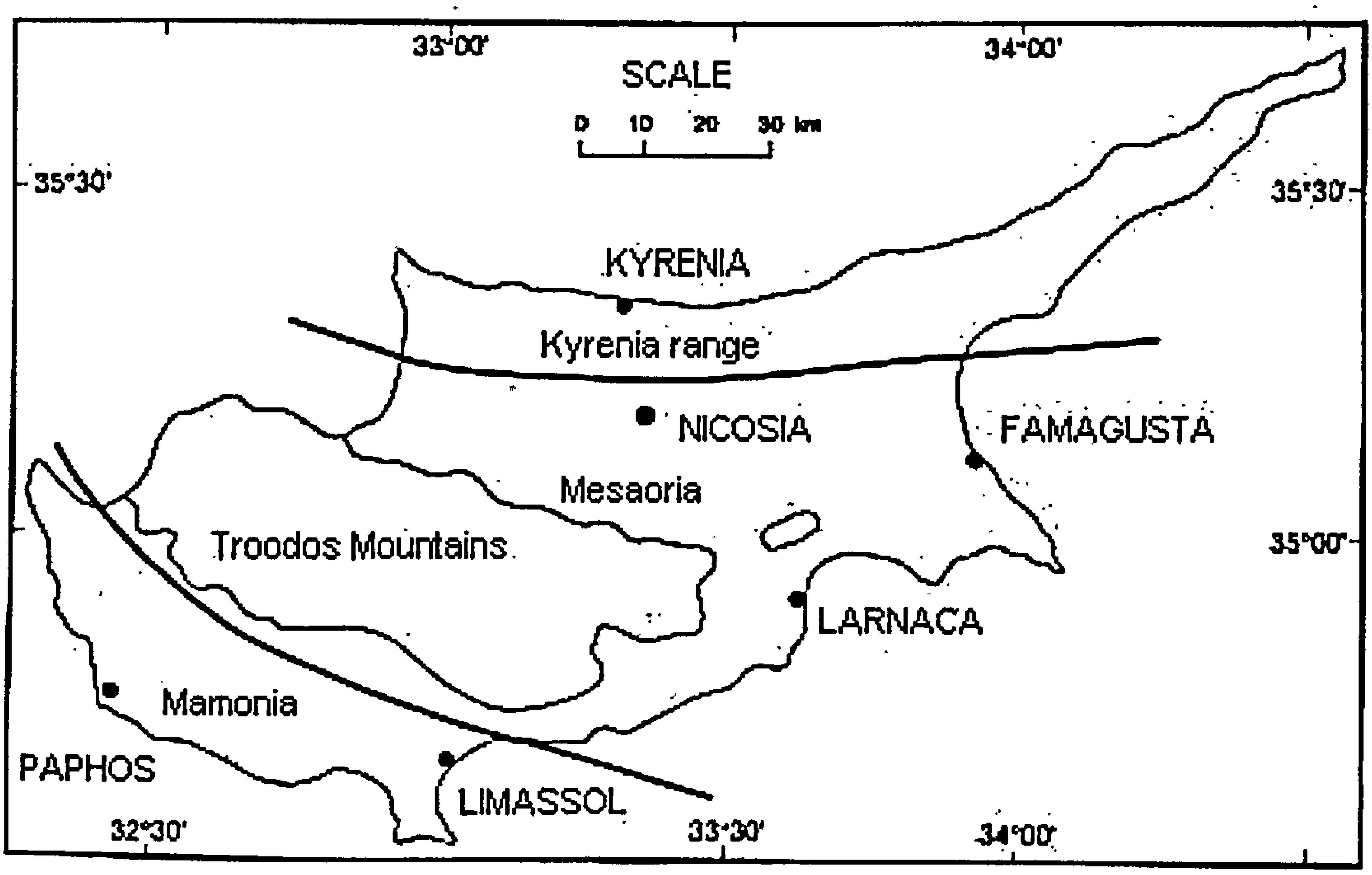


Figure 2.15. The geotectonic zones of Cyprus (after Xenophontos, 1997)

2.5.3.2 SURFACE GEOLOGY OF CYPRUS

The petrification found in the Kyrenia range consists of slices of limestones of mainly Jurassic age, serpentines, Triassic red shales, basic igneous rocks and the calcareous flysch deposits of Oligocene to Middle Miocene age which can be seen on the flanks of the narrow mountainous belt. This suggests that it was formed from a continental plate (Galanopoulos & Delibasis, 1965).

The Troodos igneous massif dominates central Cyprus and forms a structural and morphological backbone to the island. Troodos consists of an ultramafic core surrounded by basic dykes and sheet intrusives which in turn are overlain by basaltic pillow lavas and sediments (Panayidis, 1997). To the south and southwest of Troodos a wedge of volcaniclastics separates the igneous basement and the melanges, on which exotic blocks and sheets of older igneous, metamorphic and sedimentary rocks slid in. This Assemblage is often referred to as the "Mamonia Allochthonous Complex" because of its broken up and sometimes chaotic appearance in the field. The Mamonia

Complex is poorly exposed except in the southwest where erosion has removed the overlying sediments allowing the autochthonous and allochthonous rocks to be seen.

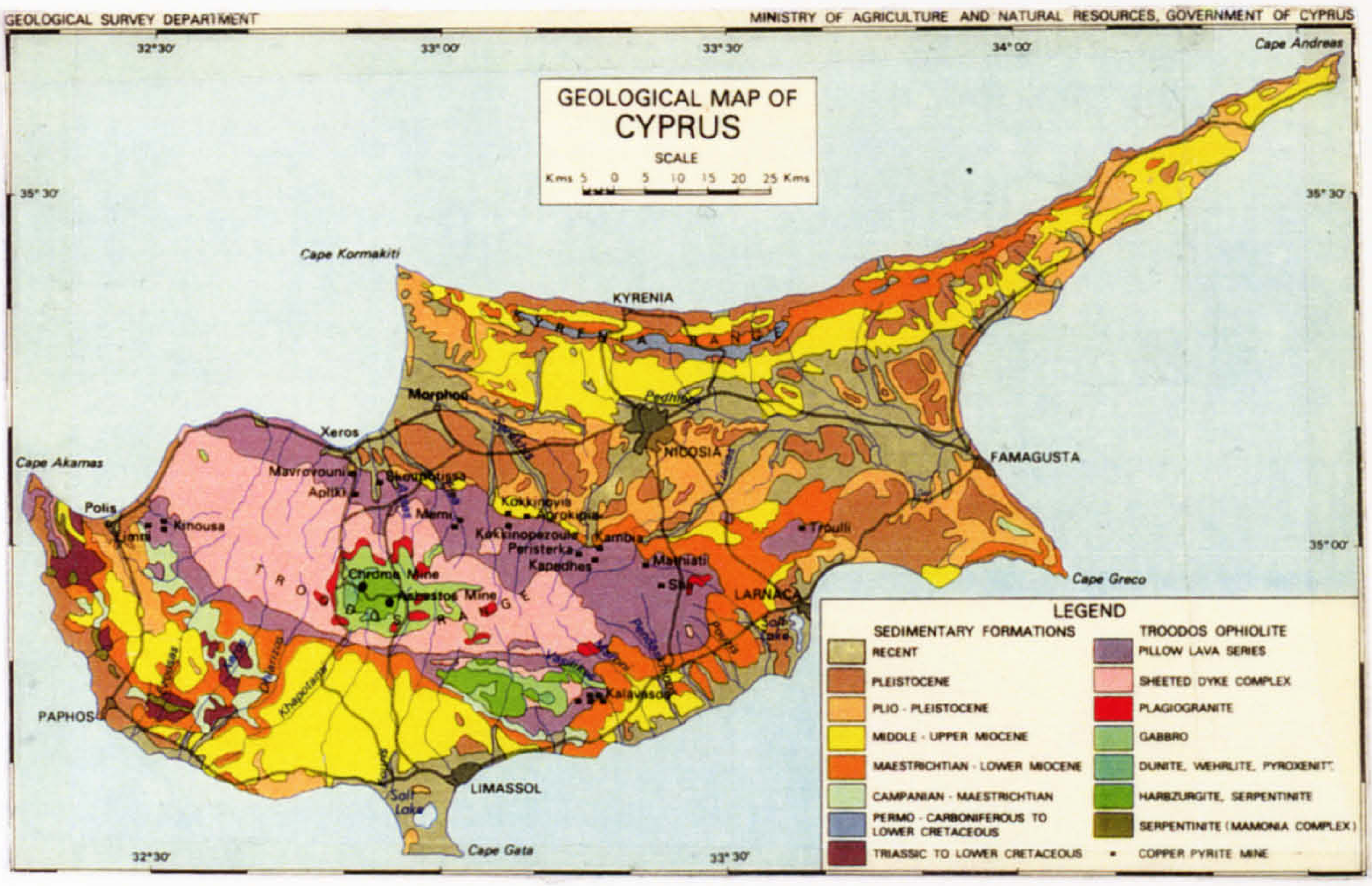


Figure 2.16. Geological Map of Cyprus (Constantinou, 1997)

The Mamonia Allochthonous Complex comprises turbiditic sandstones and siltstones intercalated with shales, cherts and packstones, alkali lavas associated with reaf and pelagic limestones, metamorphic schists, serpentines and peridotites. The total sedimentary sequence is not more than a few hundred metres thick and can be interpreted to be of deep-sea origin, but includes continental-margin elements (Hadjistavrinou and Afrodisis, 1977).

The Mesaoria plain which lies between the Kyrenia range (Pendadaktylos mountain) and the Troodos mountains, is formed by low-lying Pliocene, Pleistocene and recent sediments. Sediments of the same age are found on the south coast of the island in the form of a narrow strip (Galanopoulos & Delibasis, 1965).

The strange way in which Cyprus was formed justifies the existence of so many different kinds of strata on the island. A good knowledge of the geology of a seismically active area is essential since different kinds of soils respond in different ways during earthquakes.

2.5.3.3 Earthquake Hazards in Cyprus

Geology dependent hazards

The technogeological problems of Cyprus can be devided into 6 types:

a) Landslides
b) Rockfalls
c) Unstable slopes of mines
d) Foundation settlements
e) Liquefaction
f) Transformation of the geological formation (i.e. erosion)

Landslides

In Cyprus, reasonably big and active landslides occur mainly on the semi- mountainous to mountainous part of the Paphos district, where large areas of the Mamonia Formation are present. The Mamonia formation is highly altered and tectonized (i.e. sheared, faulted and displaced) and forms unstable conditions on steep topographic terrain. The worse areas are the ones formed by the bentonitic clays, which are very prone to swelling as well as shrinkage, consequently affecting the shear strength of the material adversely. These areas should be avoided as foundation stratum particularly on slopes. Furthermore, these clays can very easily cause landslides during earthquakes and carry down-slope any structures founded on them.

In the Limassol district the phenomenon of landslides is generally connected with the Lefkara formation or with areas with bentonitic clays. As far as the Troodos Massif is concerned due to its ophiolitic nature it does not suffer from this hazard.

In various parts of the Paphos and Limassol districts, multiple and sudden landslides which occurred as a consequence of powerful and continuous precipitation (in conjunction with rather sensitive geological formations) caused serious damage to many houses in the past, putting the lives of their occupants in real danger (Michaelides, 1997).

Strong earthquakes and active tectonics can cause sudden breakage and crushing of the rock layers and as a result the reduction of their strength. In Cyprus the worse landslides due to earthquakes, followed the 1953 event, when 158 landslides were reported in various areas of the Paphos and Limassol districts (Ambraseys and Adams, 1992). A landslide was also reported after the 1930 (M_S=5.4) earthquake in Paphos.

After the 1953 earthquake, several villages in the Paphos region at risk from landslides were relocated. Hence, it is considered that the risk from landslides is sufficiently low to be ignored in this study.

Rockfalls

On the mountainous areas of Cyprus the falling of rocks from either natural or manmade slopes is a common phenomenon. The rockfalls are mainly affected by the local geological and topographical conditions as well as by the amount of precipitation. Earthquakes can also affect rockfalls. They are usually responsible for the gradual breaking of the rock mass of the various stratas and as a result their detachment and collapse. The areas most likely to suffer are the ones over the Mamonia formation. Rockfalls were triggered during the 1896 and 1930 earthquakes.

Foundation Settlement

Settlement is the retreat of a structure due to its weight and consequently the pressurisation of the underlying soil. The geological structure and the mechanical properties of the subsoil, which supports the weight of the structure, are the main factors that affect this phenomenon. Therefore, the detailed knowledge of the geological conditions is essential in order to avoid various problems such as appearance of cracks, movement or total collapse.

Some types of soil are more prone to settlements than others. In Cyprus the main soil types likely to suffer settlement are swelling clays, coastal loose sands and organic layers and manmade landfills. The low strength (bearing capacity) of these soils can lead to high compressibility with short or long-term (especially differential) settlements of the substratum, affecting the foundation and the stability of a structure.

Foundation settlements due to earthquakes are a common phenomenon. Various cases were reported after the 1930, 1953 and 1995 earthquakes. The rapid expansion of coastal towns and tourist villages means that a larger proportion of the building stock is exposed to this risk.

Liquefaction

If an earthquake occurs in an area with soils such as uniform loose sands or/and organic layers and a high groundwater table is also present (i.e. coastal areas) liquefaction of the substratum can occur. A strong seismic loading, can minimise even further the low strength of these soils and will liquefy the beds, which will become very loose (i.e. lose their density). Consequently the buildings on them will start to suffer various types of damage such as uniform or differential settlements, bending, cracking, collapsing or a combination of all these. The 1953 earthquake triggered the liquefaction of beach deposits on the seashores, west of the jetty of Evdimou, near Pissouri and Vassa villages in the Limassol district. After the 1995 event minor cases of liquefaction were also reported in the villages of Yiolou and Yialia in the north part of the Paphos district.

TSUNAMIS

Tsunamis have struck the coasts of Cyprus several times in the past. According to Ambraseys (1963) the 76 AD earthquake, which destroyed the towns of Salamina, Larnaca and Paphos, was accompanied by a fearsome tsunami. Later on between 1202 AD and 1204 AD, Cyprus was shaken four times and a number of seismic sea-waves flooded its coasts. In 1222 AD another earthquake triggered a tsunami which flooded the towns of Paphos and Limassol. Even though there is no instrumentally recorded evidence of their strength or of the exact year they occurred, these caused significant amount of damage to Cyprus.

Fortunately, in recent years when they do occur they are usually without any significant damage. The 1896 earthquake was accompanied by a seismic wave, which agitated the sea, and the shock was strongly felt onboard ships. When the 1953 earthquake occurred, it triggered a tsunami, which hit the coast of Paphos without causing any damage. The most recent tsunami was reported during the 1995 earthquake. Fish, found on the rocks of Akamas beach suggest the occurrence of a small tsunami.

Since the tsunami risk is low, it will not be taken into account further in this study.

2.5.4 THE ATTENUATION OF THE EARTHQUAKE EFFECTS IN CYPRUS

Based on observations and theoretical considerations several attenuation formulae have been developed and published by various authors. As they vary greatly, it is difficult to agree upon a universally valid formula. Unfortunately, the data from Cyprus is insufficient for developing specific attenuation curves (Schnabel, 1987). However, for the conditions of Greece, the corresponding data and evaluations were available and appropriate attenuation curves were developed. A representative example of such curves developed by Drakopoulos (1987) is presented in (Figure 2.17). As the closest approximation for this research, the conditions of Greece would have been the best option.

However, these attenuation curves of Greece are based on average soil conditions. A detailed risk assessment should not disregard the local discontinuities. It will be therefore attempted to obtain attenuation equations which will accommodate the geology parameter.

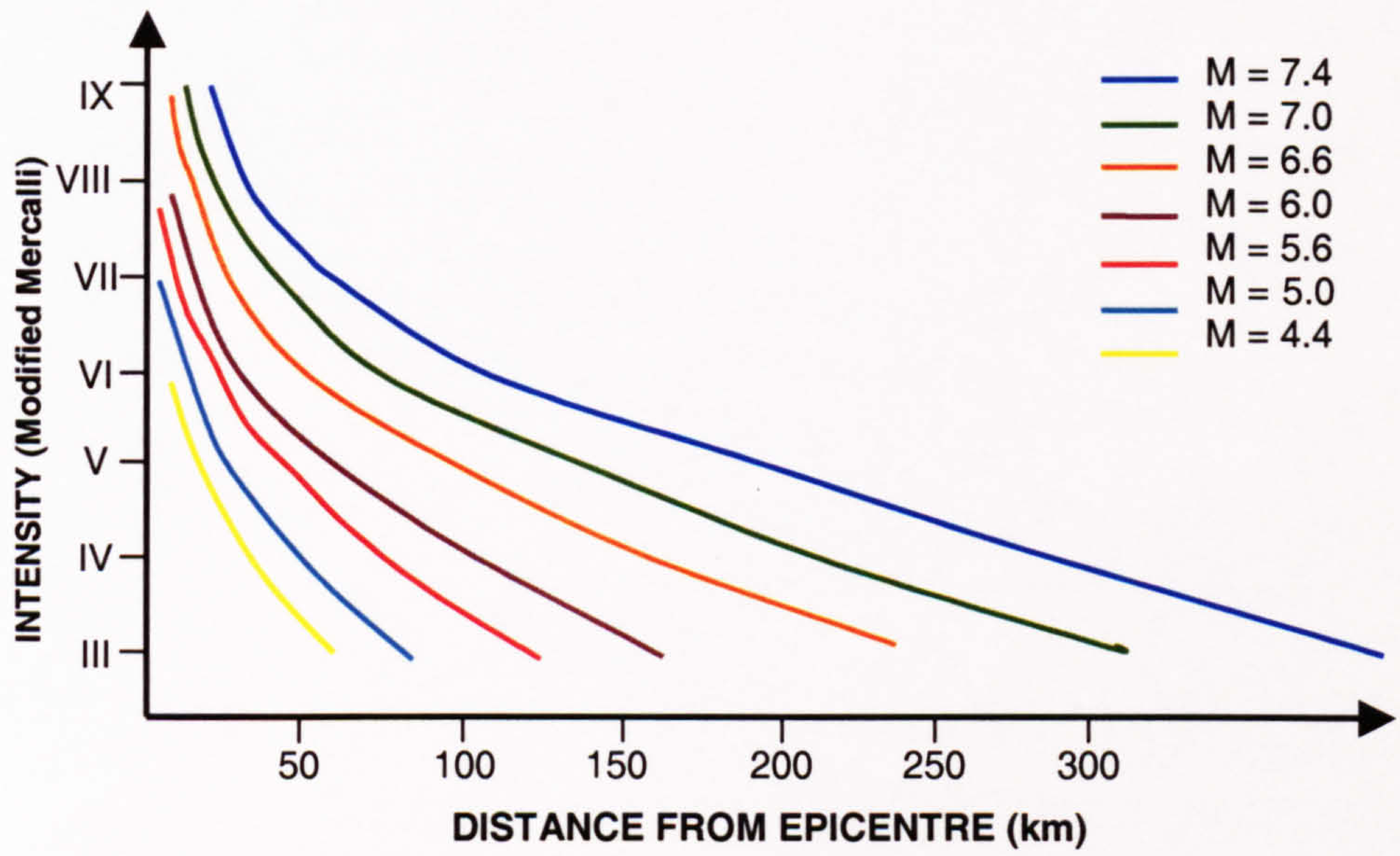


Figure 2.17. Average distances over which shocks with magnitude M are felt in the area of Greece (after Drakopoulos, 1987)

The selection of the best suited attenuation equation for the specific case of Cyprus will be considered in further detail in chapter 3. A further study of the attenuation equations will be performed when dealing with the parametric investigation of risk (chapter 5).

2.5.5 VULNERABILITY OF BUILDINGS IN CYPRUS

According to Schnabel (1987) one of the most difficult tasks he confronted during his study on the accumulation potential in Cyprus was to develop the correlation between the earthquake intensity and the extent of loss for the common buildings in the island.

Schnabel (1987) prepared a set of loss degree curves for the island of Cyprus based on a careful comparison of all the data and information available, and by taking into consideration the different building standards of various countries. Therefore, the curves are a subjective interpretation of just a few data which represent the best possible approximation of the actual conditions. However, they should not be regarded as being conservative curves, particularly for higher intensities.

For the purposes of this research it was therefore decided to obtain the earthquake vulnerability of the buildings by modifying Schnabel's loss degree curves (Figure 2.18). Figure 2.18 shows the loss degree curves, for buildings with either up to 3 storeys or 4 and more storeys as well as for industrial halls and for buildings which are classified as "standard or substandard construction" according to the Cyprus Fire tariff (Schnabel, 1987).

A more detailed analysis regarding the adopted mean damage ratios can be found in chapter 3.

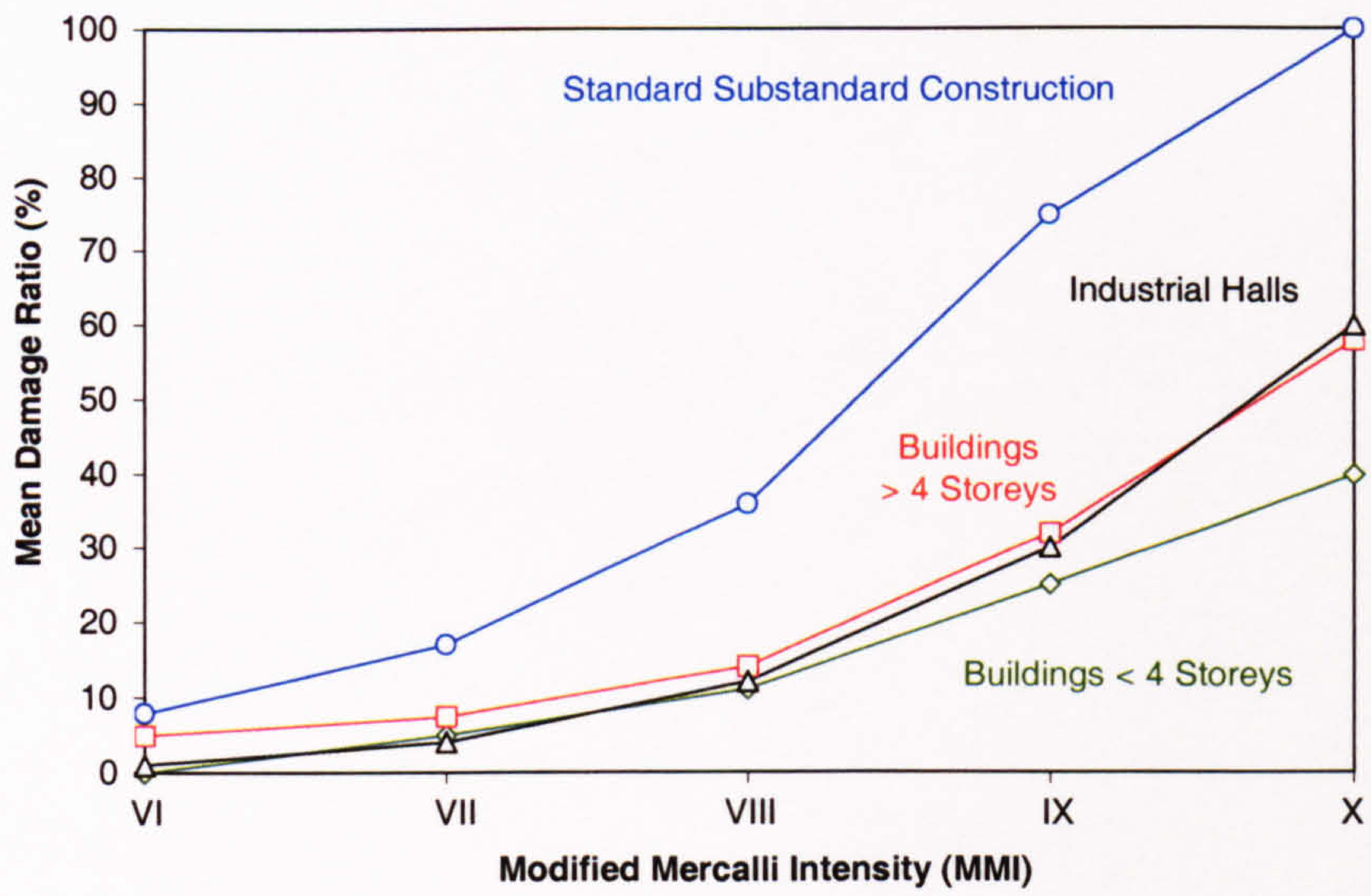


Figure 2.18. Mean Damage Ratio selected for Cyprus (after Schnabel, 1987)

2.6 DISCUSSION AND PREVIOUS ERA STUDIES

This chapter presented a literature review on the main disciplines (Seismological Aspects, ERA, Risk Management, Parameters affecting the earthquake risk in the region of Cyprus) involved in this research.

Greater attention was given to the ERA and mainly to the methods available for the evaluation of Seismic Risk.

The technology and software for preparing seismic hazard maps on regional/urban scales and for risk assessment are well established internationally. Various projects have been initiated most of them during the International Decade of Natural Disaster Reduction (IDNDR). In general the methods utilised for the seismic hazard assessment within these projects (i.e. SERGISAI, HAZUS®) are the probabilistic and the deterministic. Since the aim of this research is to assess the earthquake risk of the whole island rather than of a specific structure, it was decided that a PSHA would be adopted.

Standard procedural codes, GIS and in some cases Artificial Intelligence Techniques (i.e. SERGISAI) compose the existing models. However, these complex and high cost evaluation tools can not be used in areas of limited resources and data nor have they been proven to work.

RADIUS initiative was launched in 1996 by the secretariat of the IDNDR (1990-2000) with financial assistance from the government of Japan. It aimed to promote world – wide activities for reduction of seismic disasters in urban areas, particularly in developing countries. Limited information available (Kaneko and Sun, 2000) indicate that the proposed method is very basic and not flexible, it can not undertake probabilistic assessment.

RELEMR which started in 1992 supported by both, UNESCO and USGS, with the purpose of assessing, evaluating and reducing expected losses in the Eastern Mediterranean Region (EMR) included Cyprus. However, it was just a suggestion of theoretical procedures that should be followed and it did not propose by any means innovative ways to deal with the reduction of the earthquake losses.

The section also dealt with suggestions on various RMS which are available for the reduction of the earthquake risk.

Since Cyprus is used as an application example for the development of the model, great attention was given to the Parameters affecting the earthquake risk in the region of Cyprus. From the information presented it is apparent that there is a significant seismic hazard in the area which could potentially lead to a great disaster.

Hence, the development of an ERA framework based on the probabilistic approach will be of help for developing RMS not only to developing countries with medium seismicity around the world but in particular for the island of Cyprus which is used as a case study.

2.7 THE FRAMEWORK FOR ERA & RMS

The following two chapters deal with the development of the ERA framework, starting with collecting relevant data for undertaking this task.

The first process in any ERA is the estimation of earthquake occurrence. Historical seismicity and prediction models are examined in this chapter and used in the development of the model in chapter 4. However, when the model is used for RMS in chapter 6, in order to overcome problems of spatial distribution, Monte Carlo simulations are used to randomly generate the earthquake events.

Once particular earthquake events are generated, attenuation equations are necessary to estimate the effect of the event on specific location. These equations and their limitations are presented in section 3.2.6.

Damage that is inflicted on buildings depends on the intensity of the earthquake at a particular location as well as the vulnerability of the building. Vulnerability depends not only on the type and quality of construction but also on the age. Vulnerability is discussed in chapter 3, but the values adopted in the model are given in chapter 4.

The other necessary information for ERA is the distribution of buildings and population. The level of detail, this information is available, determines the level of accuracy of the ERA.

In the particular case of Cyprus, this information was made available at the level of administrative area (villages, towns). Hence, the model developed in chapter 4 utilises this level. However, if more detailed information become available, the model can work at a higher level.

In order to determine the human losses as a result of earthquakes, various approaches are presented in section 3.5. However, the adopted approach and values are given in chapter 4.

Chapter 4 deals with the development of the ERA model utilising the data of chapter 3 and arrives at results such as intensities, damages and human losses for specific events, which are used for calibration purposes.

The sensitivity of the model is examined parametrically in chapter 5. In order to take into account the statistical variability of the important parameters, chapter 6 uses an earthquake series which is randomly selected on the basis of Monte Carlo simulations. The simulated earthquake sequences are then used to evaluate and compare the effectiveness of various RMS.

DATA COLLECTION AND ANALYSIS

3.1 INTRODUCTION

The aim of this chapter is to present detailed information on the major aspects involved in the calculation of earthquake risk and the parameters dealing with the estimation of human life losses. The chapter is therefore divided into four main sections:

1. Hazard
2. Vulnerability
3. Value of elements at risk
4. Fatalities and Injuries

Particular attention is given to these aspects in relation to the island of Cyprus. Each aspect is examined in terms of the collection and analysis of the relevant information. Furthermore, the various assumptions made in processing the data are presented and justified. As in the previous chapter, for the sake of clarity much of the detail information is not included here but in Appendix B.

3.2 HAZARD

3.2.1 INTRODUCTION

Based on macroseismic and instrumental data, Ambraseys (1992) derived a recurrence relationship for earthquakes affecting Cyprus over the area 33.0°–37.0°N and 31.0°–35.5°E (Equation 2.4). Unfortunately, as presented in section 2.5.2.2, there are various factors that reduce the usefulness of this relationship.

In an attempt to establish a better understanding of the seismicity and eventually the seismic risk of Cyprus, the seismic data for the region was reanalysed.

3.2.2 SEISMIC DATA

A new catalogue was compiled from all the available sources of information with the more reliable data being selected for each event. The data sources used are listed below:

- *Ambraseys (1992)* The Seismicity of Cyprus. ESEE Research Report No 92-9, Imperial College, London, England.

- ***IPRG (1995)*** Seismological Bulletin of Israel (SBI) 1900-1994. Database of the Institute for Petroleum Research and Geophysics, Holon, Israel.

- ***Solomis (1998)*** Catalogue of events 1997-1998. Ministry of Agriculture, Natural Resources and Environment, Geological Survey Department, Seismological Section, Cyprus.

- ***Gajardo, et al. (1998)*** Integrated Seismic Catalogue of Cyprus 1894-1994. Seismic Microzoning of Larnaca, Cyprus. Ministry of Agriculture, Natural Resources and Environment, Geological Survey Department, Cyprus.

The newly-prepared catalogue included all the events with M_S>2.5 from 1894-1998, corresponding to a geographical area of 33.0°–37.0°N and 31.0°–35.5°E.

The four sets of data have differences as far as the record of events is concerned. The co-ordinate range for the SBI data is 32.4°–36.0°N and 32.0°–35.6°E, marginally different to that used by Ambraseys. However, many events lying within the co-ordinate ranges of both SBI and Ambraseys data catalogues were not included in both catalogues. Furthermore, in Ambraseys (1992) data, magnitude was represented as M_S (surface wave magnitude), while the SBI uses M_L (local magnitude). As far as the catalogues of Solomis (1998) and Gajardo, et al (1998) are concerned, magnitude is predominantly reported as M_L and in some cases, m_b (body wave magnitude).

3.2.3 COMPATIBILITY OF DATA

Since the four catalogues used different expressions for the representation of earthquake magnitude (M_S, M_L, m_b), a relationship between these expressions was required in order to create a uniform catalogue. It was decided to convert all magnitudes to M_S, since this is the most commonly used expression of magnitude.

The magnitude of most of the events was represented in at least two of the three magnitudes (M_S, M_L and m_b), it was therefore possible to use linear regression in order to establish relationships between the different measures of magnitude (Figure 3.1 and Figure 3.2).

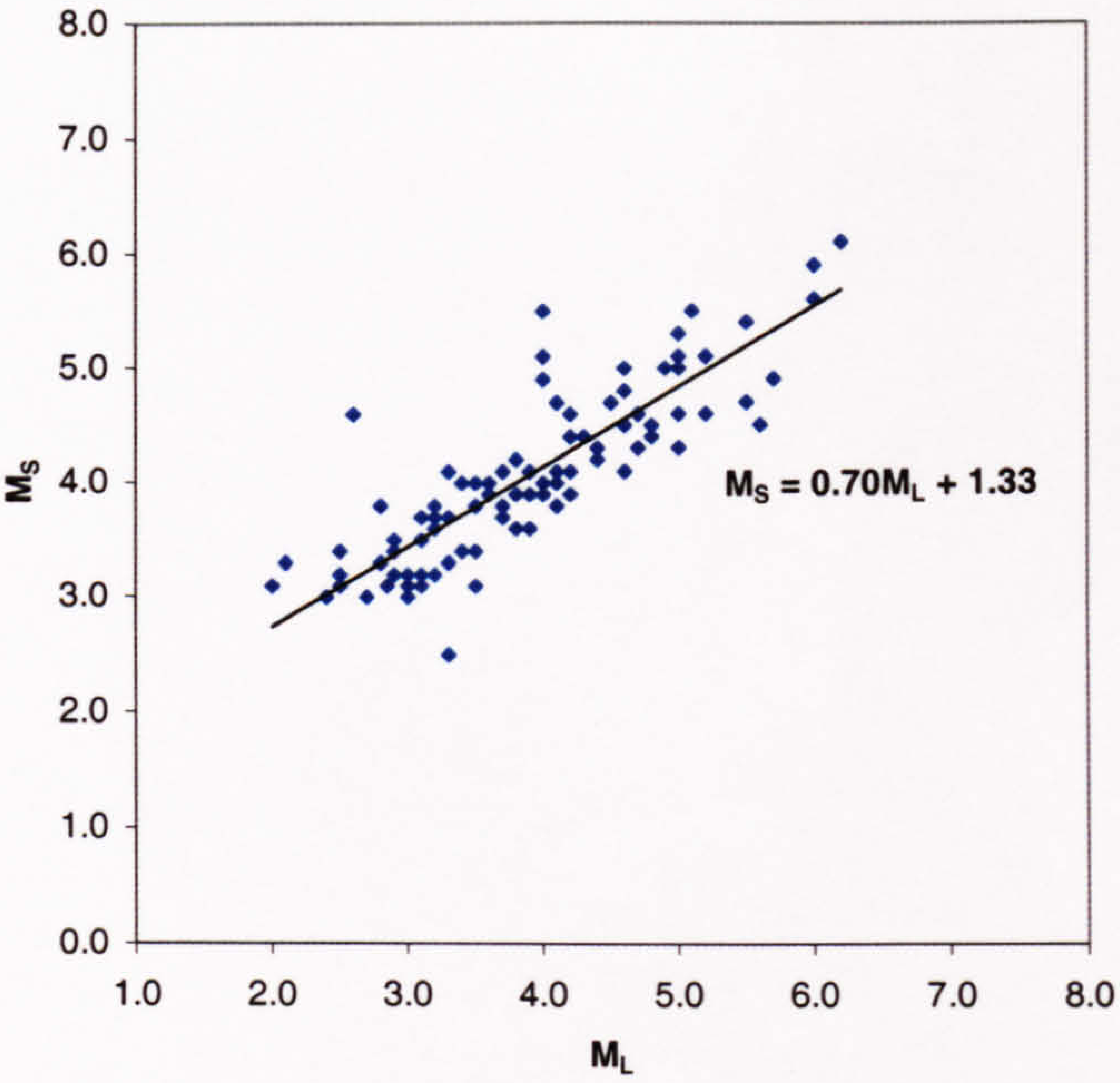


Figure 3.1. Linear Regression for the conversion of magnitudes M_L into M_S

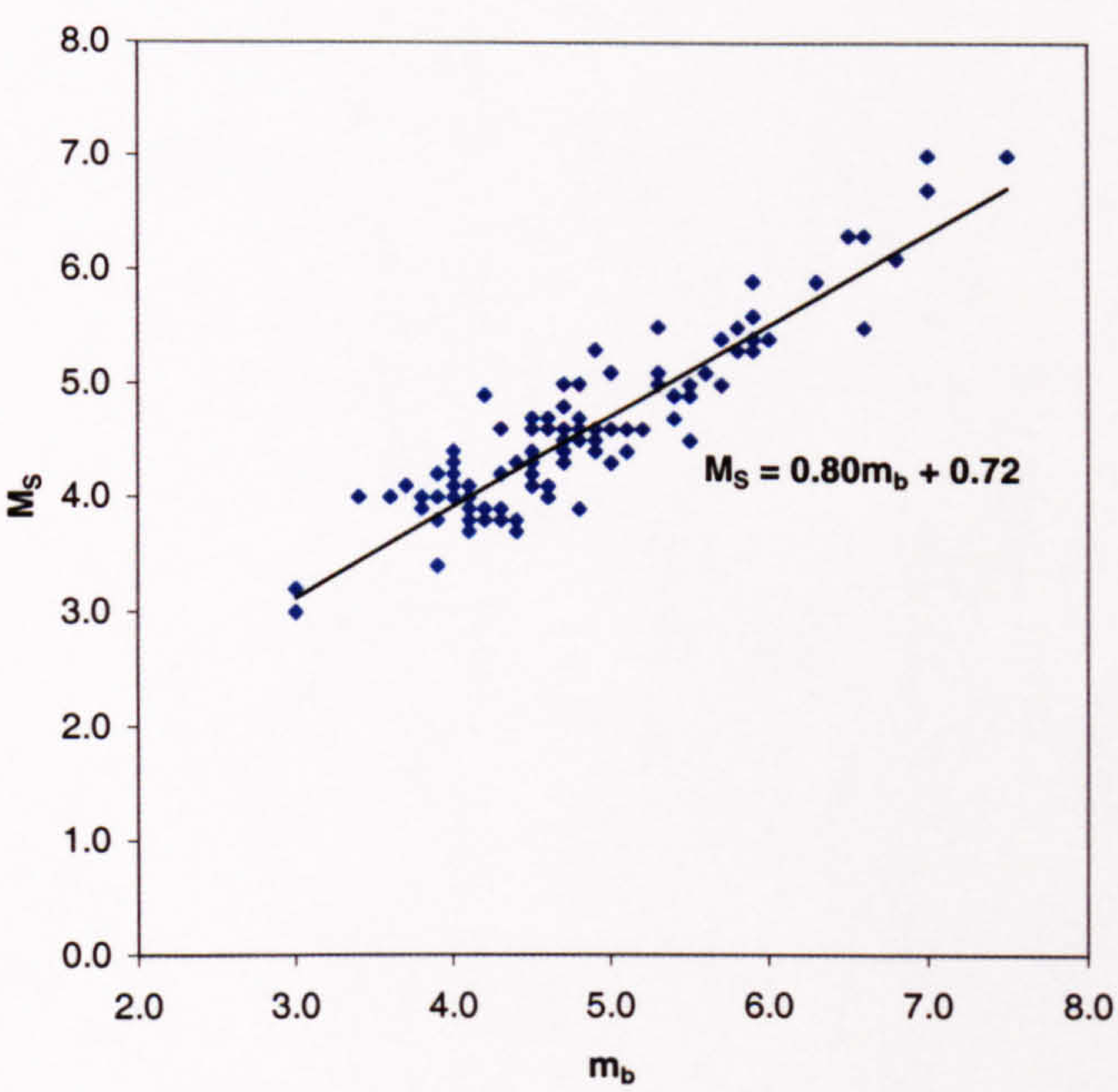


Figure 3.2. Linear Regression for the conversion of magnitudes m_b into M_S

For the conversion of the M_L and m_b into M_S the following relationships were derived:

$$M_S = 0.70M_L + 1.33 \quad \textbf{(3.1)}$$

$$M_S = 0.80m_b + 0.72 \quad \textbf{(3.2)}$$

where: M_S is the surface wave magnitude
M_L is the local magnitude
m_b is the body wave magnitude

The creation of a uniform, as far as the representation of the magnitude of the events is concerned, catalogue was achieved by applying equations 3.1 and 3.2 to the data of the catalogues and by following the rules presented in (Figure 3.3). This hierarchy of selection was based on the frequency of use of the three magnitude measures in the four data sources.

The full catalogue is presented in the Cataloque.xls file on the CD of Appendix E.

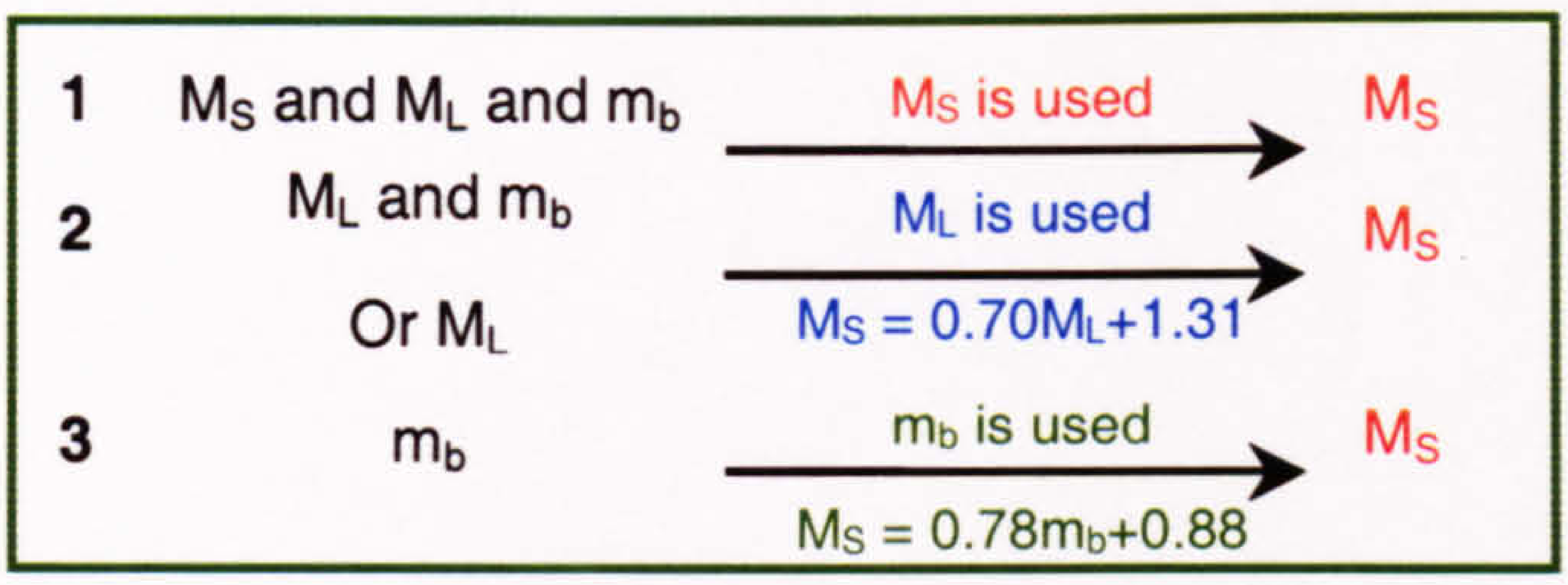


Figure 3.3. Rules followed for the preparation of the latest catalogue

3.2.4 INITIAL APPROACH

3.2.4.1 GENERAL RECURRENCE RELATIONSHIP

Using the data from 1894 until 1998, recurrence relationships, which relate surface magnitude (M_S) to log frequency (logN) of both linear and polynomial form, were derived based on the Gutenberg-Richter relationship:

The best-fit linear recurrence relationship was found to be:

$$\log N = 3.57 - 0.83 M_S \qquad \textbf{(3.3)}$$

The best-fit polynomial recurrence relationship was found to be:

$$\log N = 1.12 + 0.35 M_S - 0.13 M_S^{\,2} \qquad \textbf{(3.4)}$$

where: N is the number of earthquakes with magnitude equal to or greater than the specified M_S
M_S is the surface wave magnitude

In Figure 3.4 the derived recurrence relationships are compared with the historical data (1894-1998) and to Ambraseys' (1992) recurrence relationship and data. It can be seen that the newly derived linear fit overestimates the frequency of occurrence for the large magnitude events and underestimates the smallest events, whereas Ambraseys' equation overestimates the frequency of occurrence for both the large and small events. The polynomial curve fits the historical data better. However, in this research only the best fit linear recurrence relationship and Ambraseys relationship are examined.

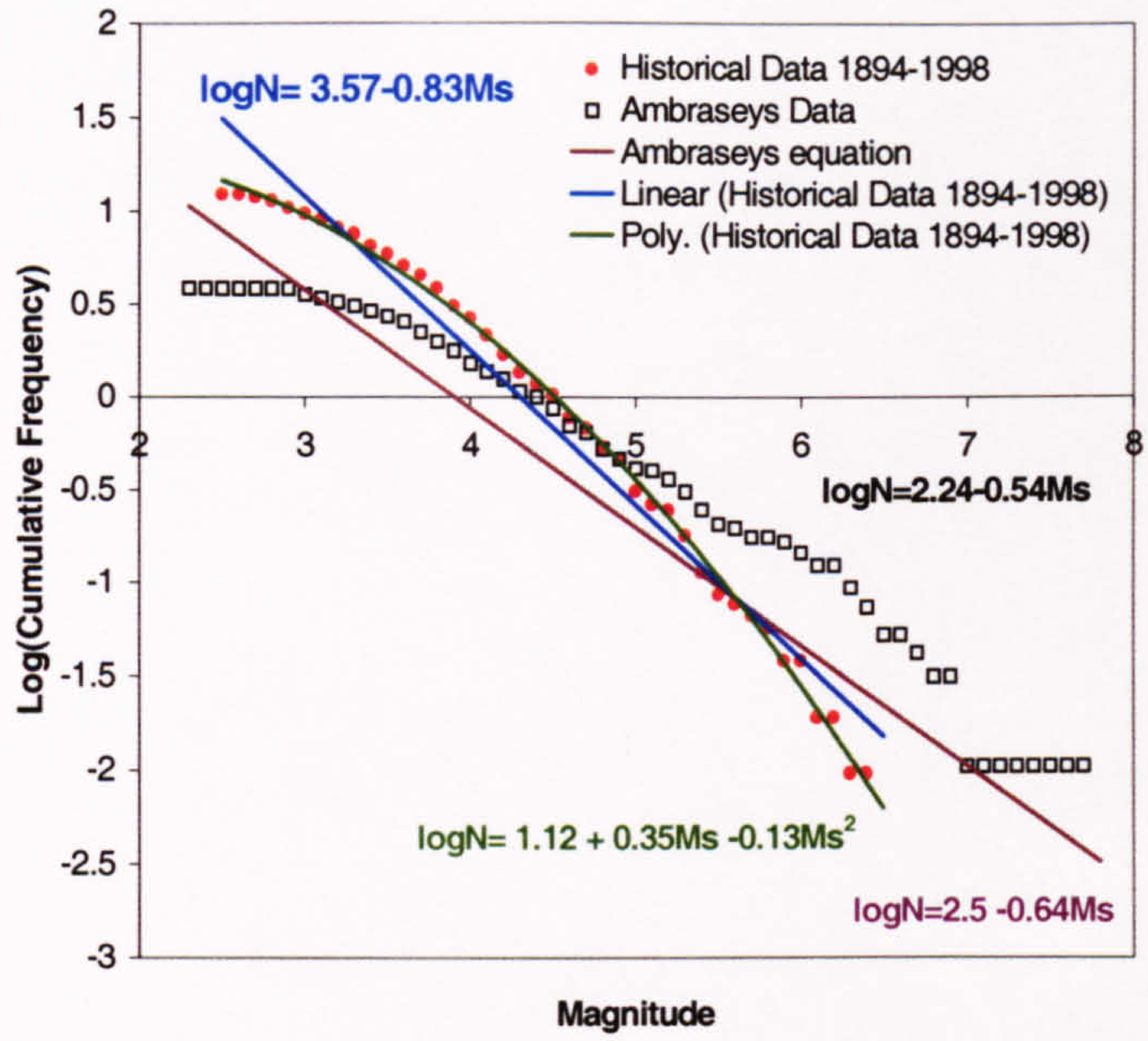


Figure 3.4. Earthquake Recurrence Relationships for Cyprus

3.2.4.2. SPATIAL DISTRIBUTION

Initial work on the spatial distribution of events has also been completed. Figure 3.5 clearly shows that the seismicity of Cyprus is not uniformly distributed. The region has been divided into three zones, 1° in latitude wide (Table 3.1).

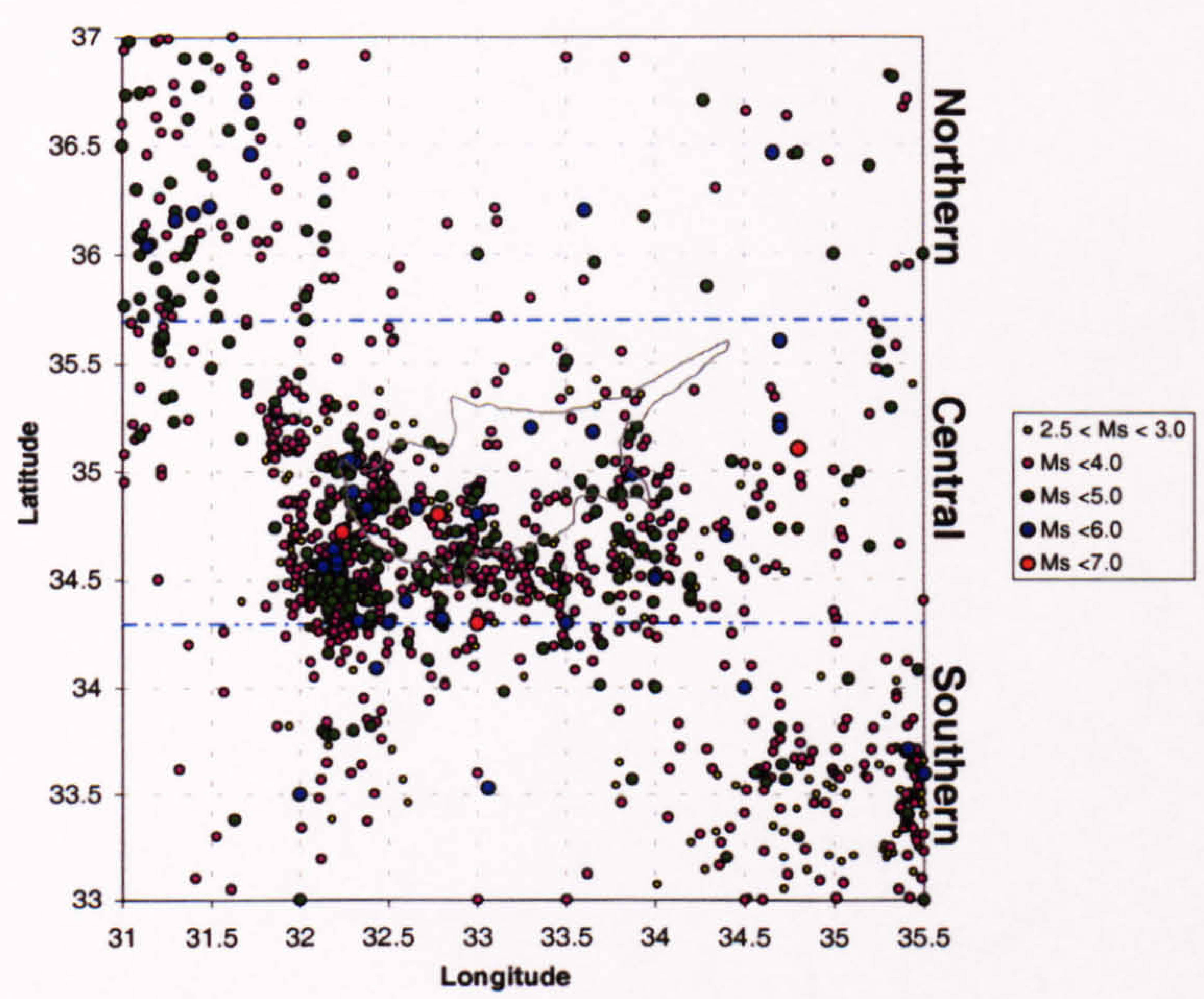


Figure 3.5. Events of magnitude >2.5 between 1894 and 1998

The recurrence relationships for each zone, using the data from 1894-1998, were found to vary significantly (Table 3.1 and Figure 3.6), with higher seismic activity associated with the Central zone. This corresponds to the position of the Cyprian Arc. The Northern zone has the lowest seismic activity.

Table 3.1. Recurrence relationships for the whole area and the three seismic zones in the region of Cyprus

ZONE	Geographical Co-ordinates	Recurrence relationship
Whole Area	33.0° - 37.0°N and 31.0° - 35.5°E	log N = 3.57 - 0.83 M_S
Southern	33.0° - 34.3°N and 31.0° - 35.5°E	log N = 2.55 - 0.75 M_S
Central	34.3° - 35.7°N and 31.0° - 35.5°E	log N = 3.19 - 0.79 M_S
Northern	35.7° - 37.0°N and 31.0° - 35.5°E	log N = 2.5 - 0.68 M_S

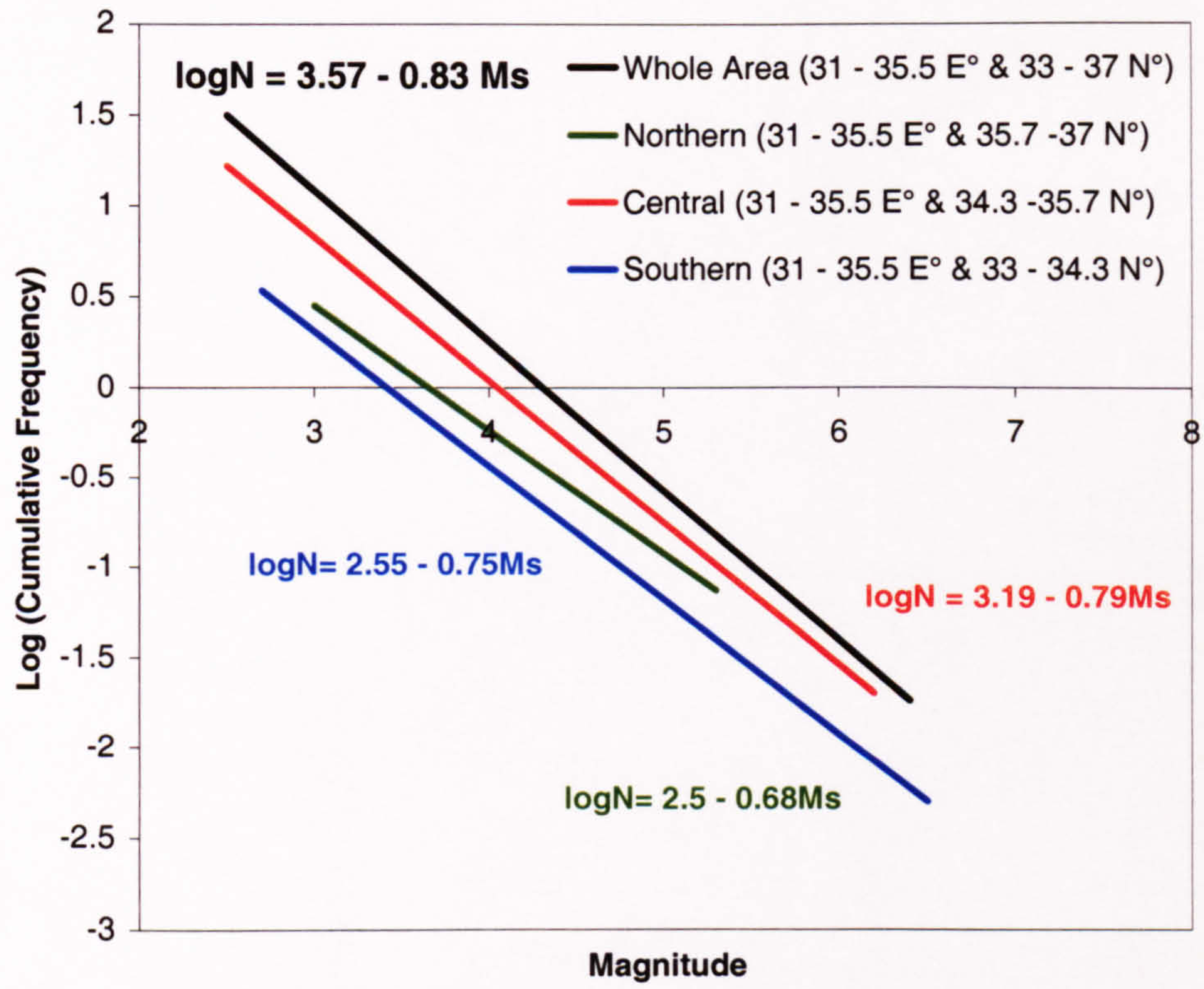


Figure 3.6. Comparison between the recurrence relationships of the whole area with the ones of the three zones (Southern, Central and Northern)

The spatial characteristics of the earthquakes will be further examined in the parametric studies presented in chapter 5.

3.2.4.3 Seismic Energy Release

The seismic energy release (E) of the historical events was approximated by using Richters' (1958) equation 3.5 and is plotted cumulatively against time in Figure 3.7.

$$\log E = 11.4 + 1.5M_S \quad \textbf{(3.5)}$$

where: E is the energy factor (ergs)

M_S is the surface wave magnitude

The cumulative energy release clearly shows that several short periods of intense seismic activity (steep portions of the graph) can be identified. Between these periods the energy release is minimal, although it does appear as if the largest energy releases are preceded by smaller releases. The time interval between consecutive periods of intense seismic energy release averages 24 years, although it may be seen that a 40-year tranquil period preceded the current phase of intense seismic activity.

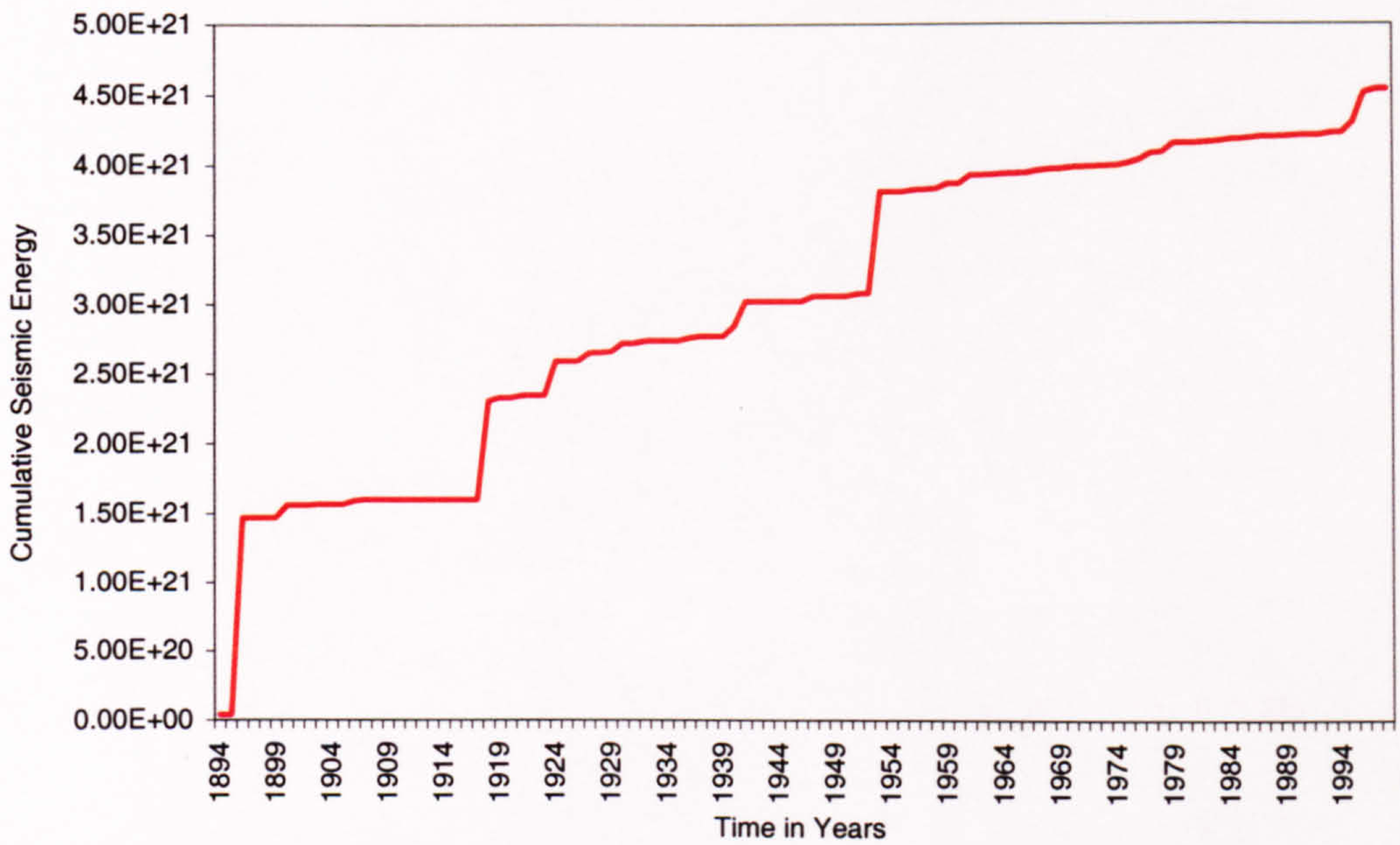


Figure 3.7. Cumulative seismic energy release from 1894 until 1998

The calculated energy release was compared with the energy release predicted using Ambraseys' recurrence relationship and the two (linear and polynomial) recurrence relationships derived using the data from 1894-1998 (equations 3.3 and 3.4). The recurrence relationships were used to estimate the number of events per year with magnitude equal or greater than M_S and the return period in years. These were required in order to find what was the annual probability of occurrence and eventually the non cumulative probability of occurrence for each M_S. The non cumulative probability was then multiplied with the energy release which was estimated using Richter's equation (equation 3.5). In each case of predicted energy it was assumed that no events with $M_S > 6.5$ would occur. This assumption was based on the fact that no earthquakes of a higher magnitude have been recorded in this region to date. Figure 3.8 suggests that Ambraseys' recurrence relationship overestimates the energy released. This is clearly a result of the fact that this relationship over-predicted the frequency of occurrence of large events. The current level of energy released falls exactly on the value predicted by equation 3.4.

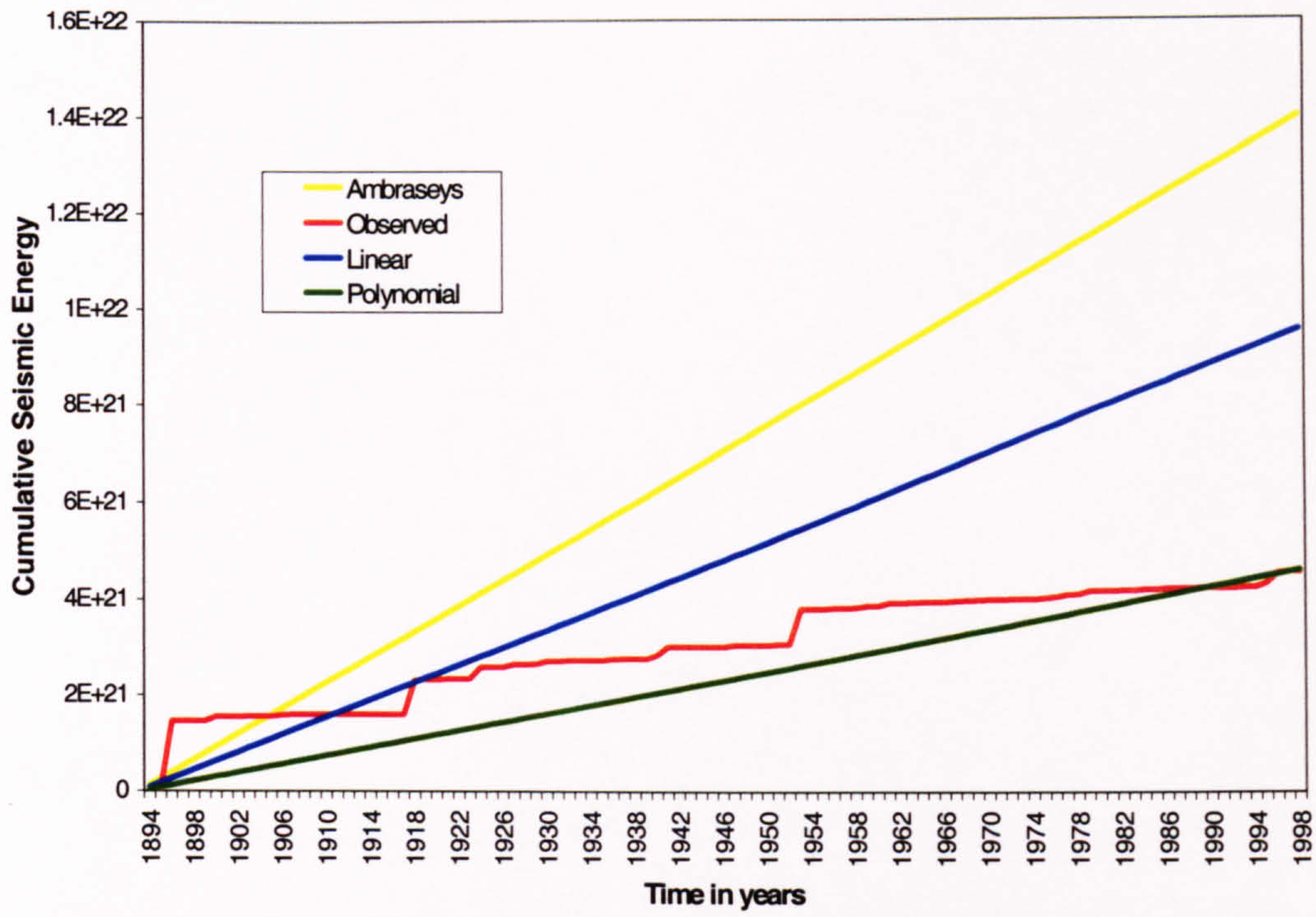


Figure 3.8. A comparison of the observed energy release and the energy release predicted by recurrence relationships

On average, the seismic energy release for the area of Cyprus is 4.32 x 10^{19} ergs per year.

3.2.4.4 SPATIAL ASPECTS OF THE HISTORICAL RECORD

In addition to the identification of periods in time which have been subject to intense seismic energy release, the spatial distribution of energy release was considered.

Figure 3.9, which was prepared using the data from 1919 until 1995, shows that the distribution of energy in space is not uniform. In the immediate vicinity of Cyprus the energy appears to be concentrated around two arcs, one following the line of the south coast, and the other parallel to it but nearly 1° latitude further south. This data may be compared with the existing theories relating to the structure of the Cyprian Arc. If the Cyprian Arc is a plate boundary, then either a single arc, or possibly two parallel arcs, would be expected. If there is only a single arc, then the low energy release noted at 34.2°N, 33.2°E could represent a seismic gap. There would be an enhanced probability associated with future large events occurring in this area. On the other hand, if the arc is actually composed of two parallel fault lines, then the gap would represent a genuine zone of low seismic activity. Equally, this evidence does not contradict the theory

(Galanopoulos and Delibasis, 1965) that the Cyprian Arc corresponds to a broad zone of thrusting.

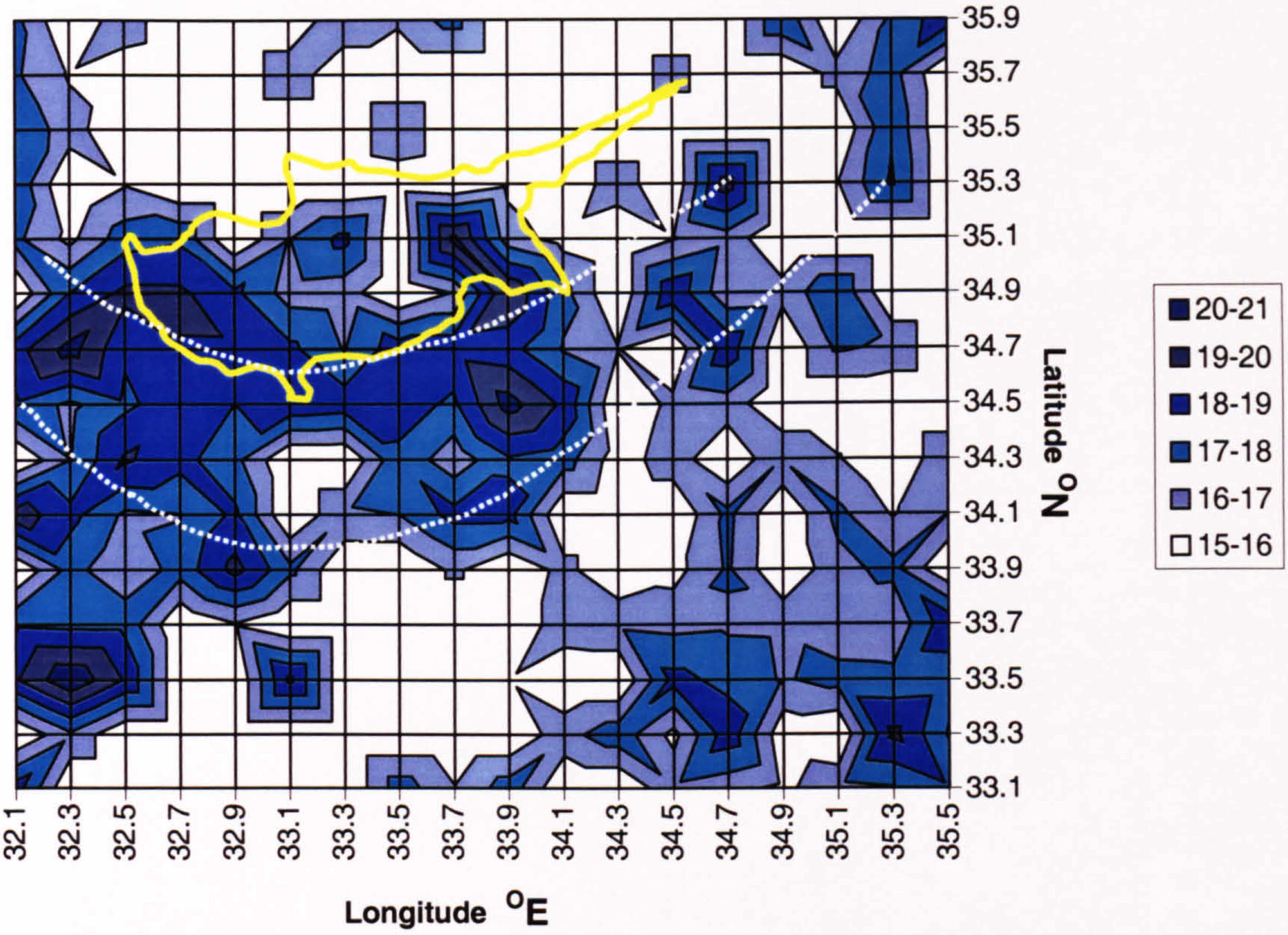


Figure 3.9. Spatial distribution of energy released in the area of Cyprus from 1919 until 1995 (Kythreoti et al., 1997)

Further analysis using the latest catalogue (1894-1998) showed the same results. The annual seismic energy release will be compared to the annual damage cost at a later stage.

3.2.4.5 Depth

By examining the depth of the earthquakes it was expected that the results would show that shallow earthquakes occur in the sea area south of Cyprus and closer to the island they become deeper. If this was true then the Earthquake Hazard would be less than what would be predicted by equations which assume uniform but shallow depth distribution. This expectation was based on the Global Tectonics of the area where the Northern part of the Eastern Mediterranean basin which includes Cyprus is uplifted due to the continental collision between the Anatolian and Africa-Arabia plates as shown in Figure 3.10. According to Biju-Duval and Montadert (1976) continental subduction occurs just on the south of the island along the position of the Cyprian Arc.

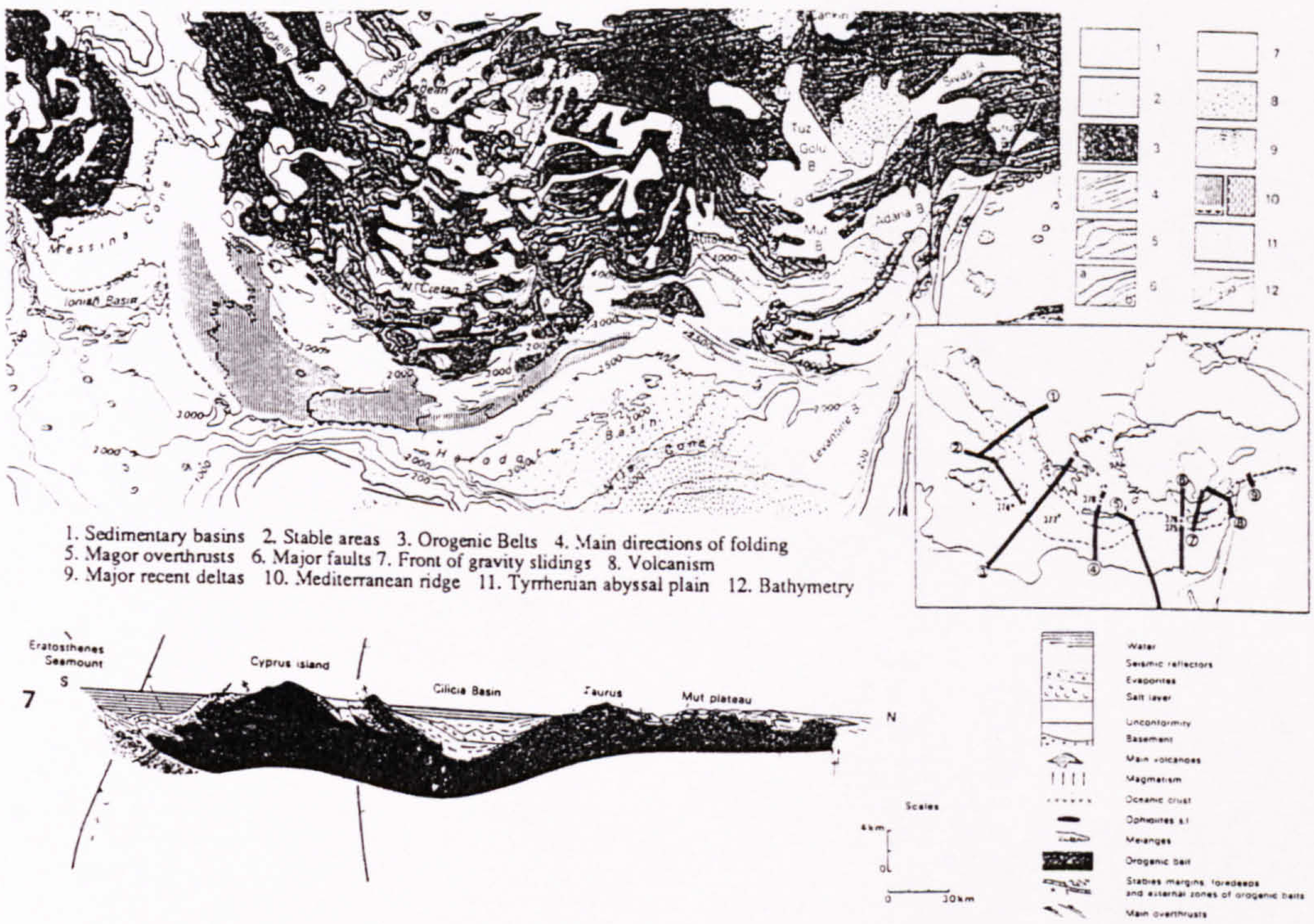


Figure 3.10. Structural Map of Eastern Mediterranean Area (Reproduced from Figs 1 & 3 of Biju-Duval and Montadert, 1976)

Furthermore this study was performed in order to determine whether the Benioff zone theory, which suggests that if the earthquakes near island arcs are compared with their depths the presence of a dipping seismic zone emerges, applies for the case of Cyprus.

The study considered only the earthquake events around the likely position of the Cyprian Arc of magnitude $M_S>4.0$.

An arbitrary point representing the centre of rotation of the Cyprus Arc was selected (Figure 3.11). The distances between the centre of rotation and the epicentres of the earthquake events under consideration are plotted against the depths of the earthquakes in Figure 3.12. The whole procedure was repeated for a number of different arbitrary centres (Section 1 - Appendix B) to examine this hypothesis. The expected results based on the theories discussed above would be to observe a dipping trend along the line of the subduction zone.

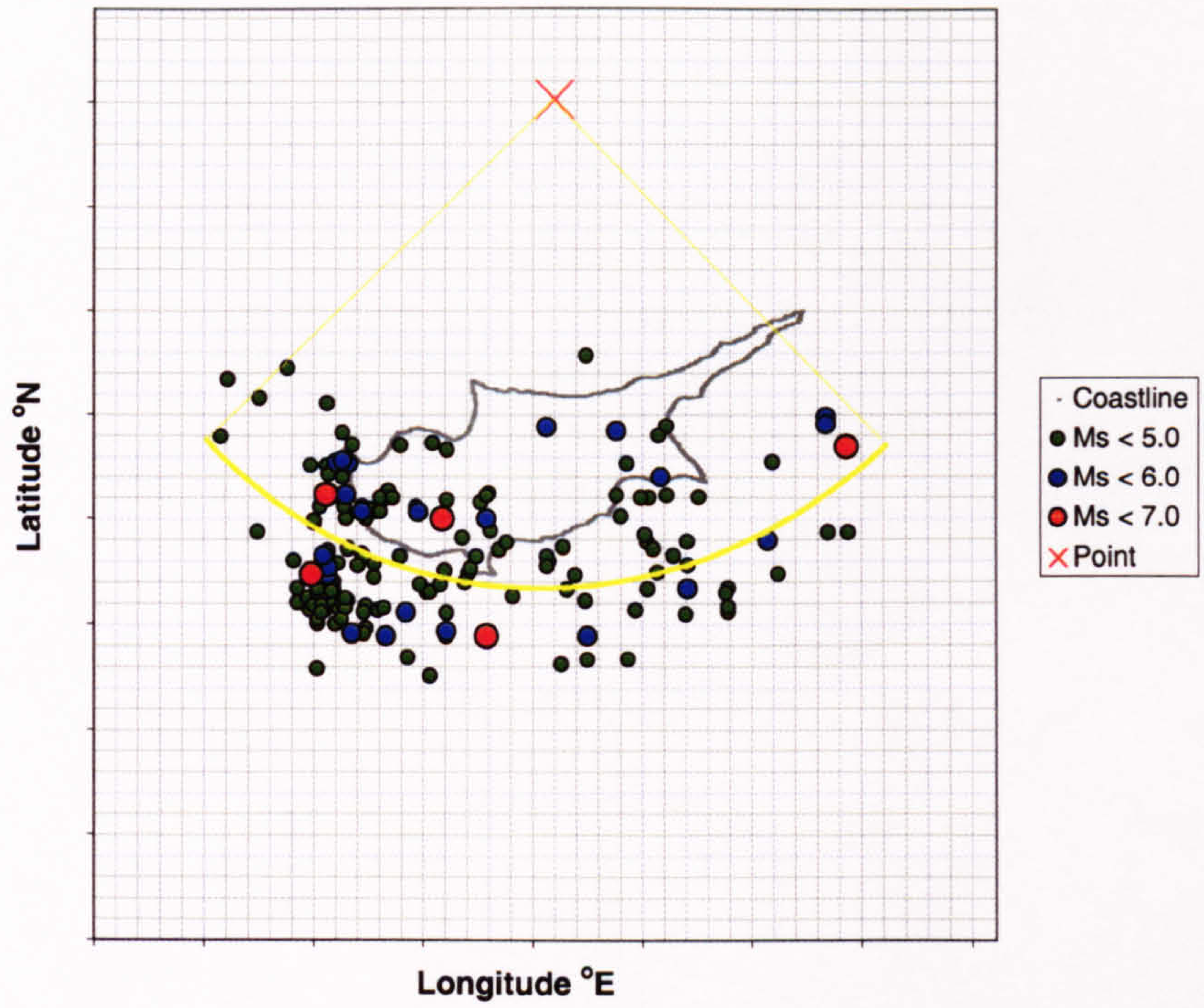


Figure 3.11. First arbitrary centre of rotation selected for the examination of the depth

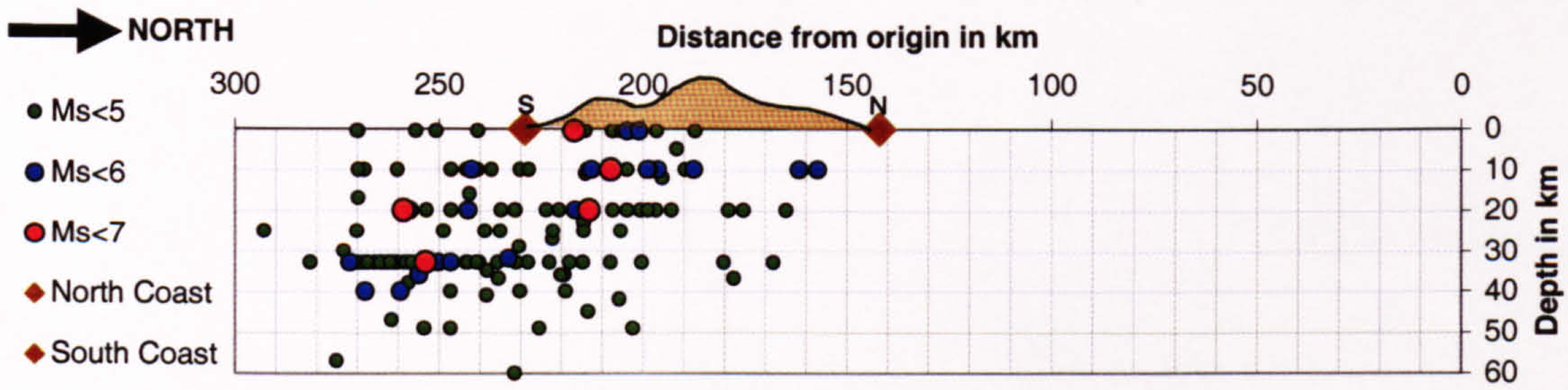


Figure 3.12. Depth distribution of earthquakes with magnitude M_S>4.0 for the area around the position of the Cyprian Arc

However, from the resulting charts an interesting pattern appeared. The presence of a dipping zone is obvious, but in an opposite direction to that of the subduction (i.e. suggesting Eurasian plate dipping under the African plate). At this point it must be stated that it is well appreciated that there are limitations in the identification of the epicentre and the depth of the earthquake events and that there might be errors in the record of earthquakes used.

Further study of the earthquake records showed that the earthquakes that caused significant damage to the island (M_S>6), were shallow (d<60km) earthquakes (Figure 3.13). However, this can not be considered as a rule since earthquakes with a return period of greater than 100 years are not represented in the catalogue examined.

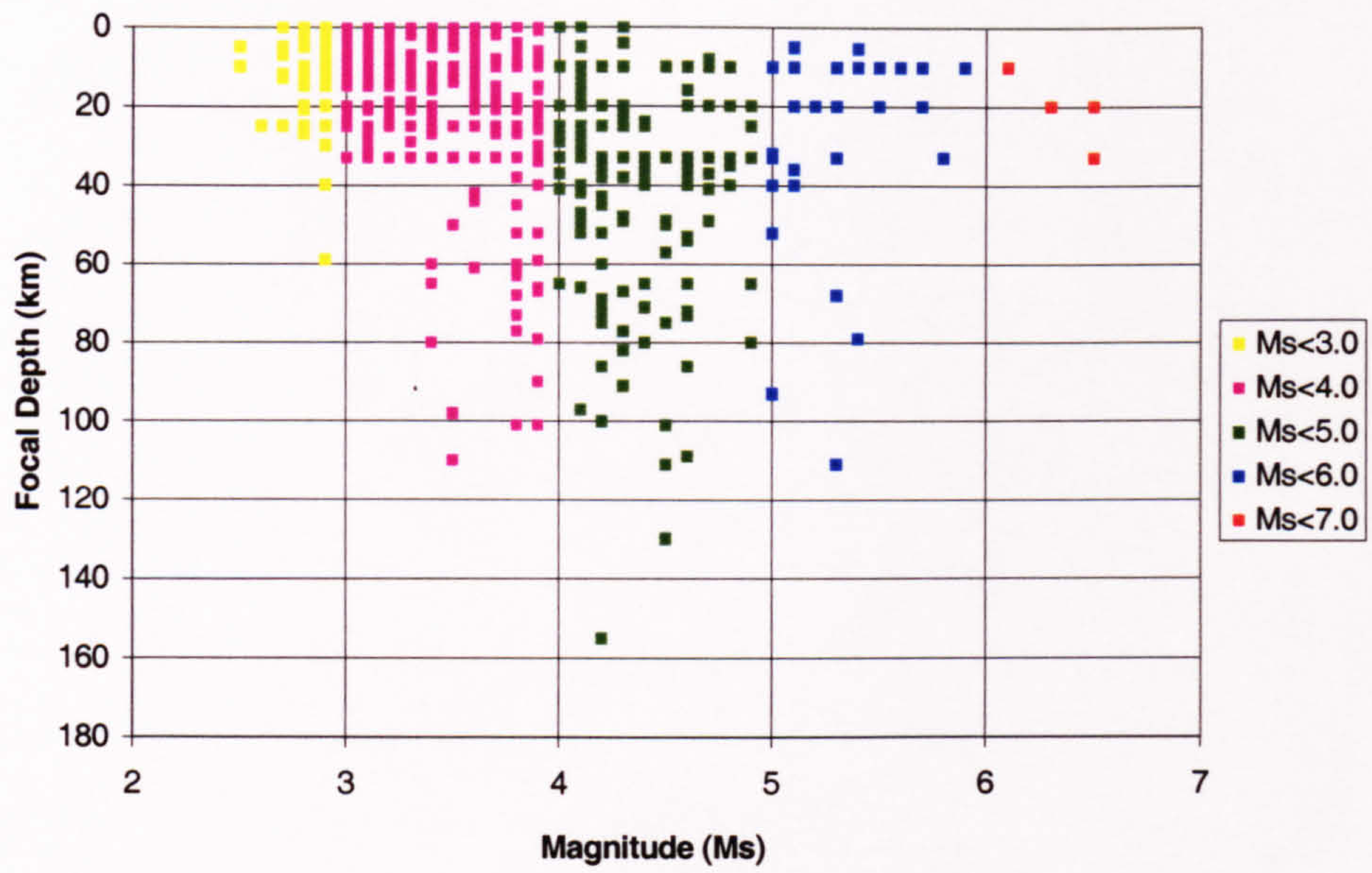


Figure 3.13. Earthquake magnitude (M_S) Vs Earthquake Focal Depth for the Earthquake Catalogue of Cyprus 1894-1998

Though the above results are interesting, they are not conclusive. It was decided not to progress further in this field, since this research is dealing with the production of an effective simulator and not the in-depth examination and analysis of the seismicity. However, the depth uncertainty will be studied as part of the parametric studies in chapter 5.

3.2.5 FINAL AMENDMENTS TO THE EARTHQUAKE CATALOGUE

Papazachos and Papaioannou (1999) presented a new earthquake catalogue for Cyprus by using data from more seismological stations claiming a better accuracy for stronger events. Therefore, the catalogue compiled by them, which became available at a late stage of the research, was regarded to be more detailed and accurate than the one initially adopted based on Ambraseys (1992), the SBI (1995), Solomis (1999) and Gajardo, et al. (1998).

By studying the two data sets it was established that as far as the magnitude determination is concerned, they had some significant differences whereas surprisingly the epicentral locations were similar. Some differences were also found regarding the depths of the earthquakes.

Since Papazachos and Papaioannou (1999) use moment magnitude M_w the appropriate relationship was obtained from Papazachos et al (1997) and was used to transform the

M_w to M_S (Section 2.1 - Appendix B). The two catalogues were combined, using the latest results when there was a conflict.

3.2.6 ATTENUATION EQUATIONS

This section deals with the identification of the most relevant attenuation equations for both Peak Ground Acceleration (PGA) and Modified Mercalli Intensity (MMI). Once the various equations, with their characteristics as well as limits to application, are introduced the geology effect on the attenuation of the seismic waves will be addressed. Finally, based on a comparison of the different equations, the most suitable is selected for the purposes of this research.

Strong-motion attenuation equations (i.e. PGA equations) are considered a very important parameter for any earthquake hazard analysis and are very significant in determining the resulting earthquake design loads (Ambraseys and Bommer, 1995). Despite the fact that the number of strong-motion accelerographs has been increasing, for some hazard and risk assessment purposes the intensity scales remain an important measure of strength of ground shaking in earthquakes (Dowrick, 1992).

There is a large number of attenuation relationships available for both PGA and intensity, which enables the most appropriate or the most convenient equation for each particular situation to be selected. One of the main criteria for the selection and application of an attenuation law is that the seismological and strong-motion input data have been completely reconsidered and published and that they are typical of the seismotectonic environment of the area under consideration (Ambraseys and Bommer, 1995).

As far as this research is concerned it has been decided that both the PGA and MMI will be examined.

3.2.6.1 ATTENUATION LAWS FOR PGA

Concerning the attenuation relations for Cyprus, the best solution would be relations based on strong motion data (Theodulidis, 1999). At the present time there is no such data bank for the island. In such cases, attenuation relations based on data from comparable seismotectonic environments are adopted. Selected equations are presented in Table 3.2. One suitable set, could be the relations (equations 3a and 3b in Table 3.2) proposed for the area of Greece (Theodulidis and Papazachos, 1992). Other equations

2a and 2b (Ambraseys and Bommer, 1991) or equation 5 (Ambraseys, Simpson and Bommer, 1996) derived based on data obtained from earthquakes in Greece as well as areas of similar seismotectonic environments have been obtained and are listed below. Table 3.2, presents the units of acceleration and the definitions of earthquake magnitude, M, and source-site distance, R (km) as well as their limits of application. All the equations are listed in Section 2.1 of Appendix B.

Table 3.2. Characteristics of the attenuation equations

No	Units	No events	h max	M	Mmin	Mmax	R	Rmin	Rmax
1	cm/s^2	58	15	M_L	3.5	5.0	r_e	5	30
2a	g	529	25	M_S	4.0	7.3	d_f	1	313
2b	g	529	25	M_S	4.0	7.3	r_f	1	313
3a	cm/s^2	40	18	M_S	4.5	7.5	d_e	1	130
3b	cm/s^2	28	159	M_W, M_{JMA}	5.2	8.0	r_e	40	230
4a	g	1260	25	M_S	2.0	7.3	d_f	1	313
4b	g	828	25	M_S	4.0	7.3	r_f	1	313
4c	g	145	25	M_S	4.0	7.3	d_f	1	45
5	g	157	30	M_S	5.0	7.5	d_f	1	200

Source Distances can be epicentral (d_e), hypocentral (r_e), closest horizontal distance to the projection of the fault rupture at the surface (d_f) or to a horizontal plane at the focal depth (r_f).

Magnitudes can be surface wave magnitude (M_S), local magnitude (M_L), Japan meteorological agency magnitude (M_{JMA}).

The obtained equations were analysed and compared and their limitations are discussed (Section 2.3.2 - Appendix B). All had their advantages and disadvantages and it was very difficult to identify one completely suitable for use in the case of Cyprus. Despite the difficulties, it was decided that Theodulidis and Papazachos (1992) offered the most consistent set of equations for the island of Cyprus (3a and 3b in Table 3.2). The decision was mainly based on the constraints of the equations, which made them applicable for all the data of the earthquake catalogue of the island. Furthermore, the fact that this equation set included an equation which relates the accelerations to intensities contributed to the selection of this set.

Theodulidis (2000) commented that equations 3a and 3b are very reliable for alluvial sites. As far as the anelastic attenuation (Section 1.1.2.1 - Appendix A) is concerned Theodulidis (2000) suggested that the (–1.65) factor in equation 3a includes both the geometrical and anelastic attenuation. An individual factor was not assigned to the anelastic attenuation due to the fact that the sample of data used was very small and the resulting value of the factor would be equally very small.

3.2.6.2 ATTENUATION LAWS FOR I_{MM}

According to Bommer (2000) any equation relating PGA to MMI is at best extremely approximate and furthermore there is no physical reason at all why there should be any direct correlation between the two parameters. Though that statement is true due to the variability of ground conditions and building characteristics, if these two parameters were accounted for, then a relation between PGA and Intensity should be possible. For the purposes of this research, it is essential to have models that predict Intensity values since the only available data for Cyprus regarding the Earthquake Response and damage are a function of MMI. Future work should concentrate in developing vulnerability relations based on expected ground accelerations.

The availability of intensity attenuation equations is rather limited compared with those for acceleration. Only one equation (3.6) was found for a similar region and was derived based on earthquakes in Greece (Theodulidis and Papazachos, 1992).

$$\ln a_g = 0.28 + 0.67 I_{MM} + 0.42S + 0.59P \tag{3.6}$$

where: α_g is Peak ground acceleration
I_{MM} is Modified Mercalli Intensity
S is Soil characterisation is equal to zero at alluvial sites and one at rock sites
P is equal to zero for 50 percentile values and equal to one for 84 percentile values

Other equations for the calculation of the Intensity were also obtained, but the source of the earthquake data used for their derivation was either the USA or the New Zealand. These equations are presented in Section 2.2 of Appendix B.

As far as the intensity attenuation is concerned, the equation derived by Theodulidis and Papazachos (1992) which transforms the acceleration to intensity will be used. The use of the equation is free from any constrains since it was derived based on observations and it is not dependent on the equations derived for the estimation of the acceleration (3a and 3b).

3.2.6.3 GEOLOGICAL INFLUENCE ON ACCELERATION AND INTENSITY: AMPLIFICATION OR ATTENUATION

One major factor which affects the attenuation of the seismic waves is ground geology. The effect of the geology can be taken into consideration either when the PGA or MMI are calculated (equations 3a, 3b, 4c, 5 – Section 2.1 - Appendix B), or if they have been estimated for rock they can be adjusted appropriately. This section deals with the classification and the analysis of geology.

According to Ambraseys and Bommer (1995) there is no common definition of site classification and contradictory models exist. For example in Figure 3.14, one model has predicted a soil site of having higher accelerations (Sabetta and Pugliese, 1987) whereas another one predicts higher accelerations on rock (Theodulidis and Papazachos, 1992). Therefore, it can be concluded that this simple approach to soil classification (S=0 for soil and S=1 for rock) is not objective and site effect results must be used with care.

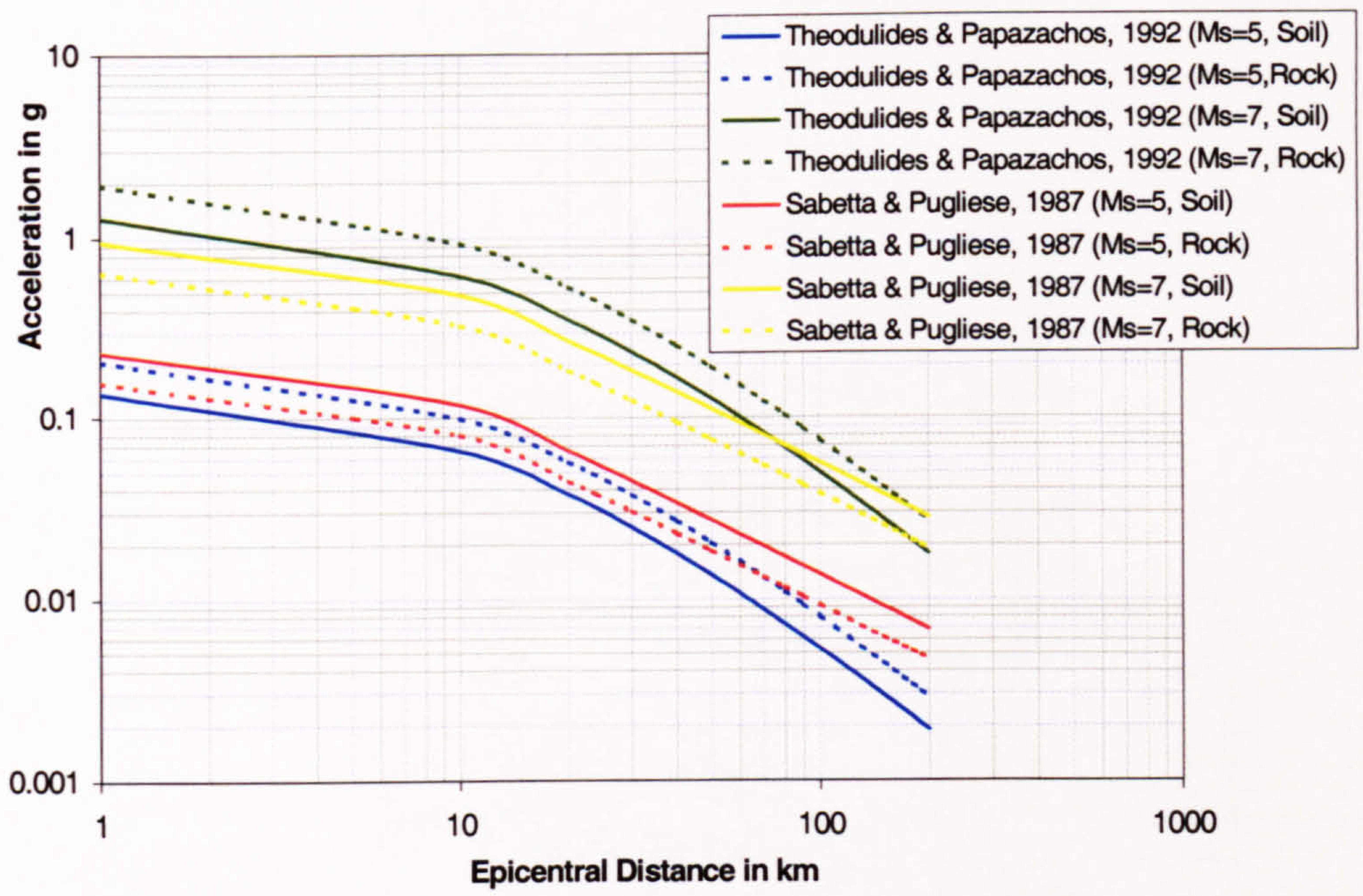


Figure 3.14. PGA predictions from European attenuation equations for rock and soil (after Ambraseys and Bommer, 1995)

A different way to improve the classification of the local geology is by using the shear-wave velocity to model the site effects (Ambraseys and Bommer 1995). Unfortunately, in the case of Cyprus, information on the shear-wave velocity is not available and therefore for the current data the only solution is to either use the Soil characterisation (S) values or once the Intensity is calculated to use a value that modifies, the I_{MM}.

Based on the Geological Map of Cyprus, nine main formations were identified and numbered from 1-9. The appropriate formation number was then assigned to each village or town as shown in Table 3.4 which was prepared based on information of the geological map of Cyprus (Figure 2.16) and other literature obtained from the Geological Survey Department of Cyprus. A cruder map, which can be found in the

Geology of Cyprus Report 10, was also used to simplify the whole process. By comparing the Geological Map of Cyprus to Figure 3.15, a similar colour distribution of the geological types can be observed, which even though it is not a quantitative check it verifies the soil type assignment.

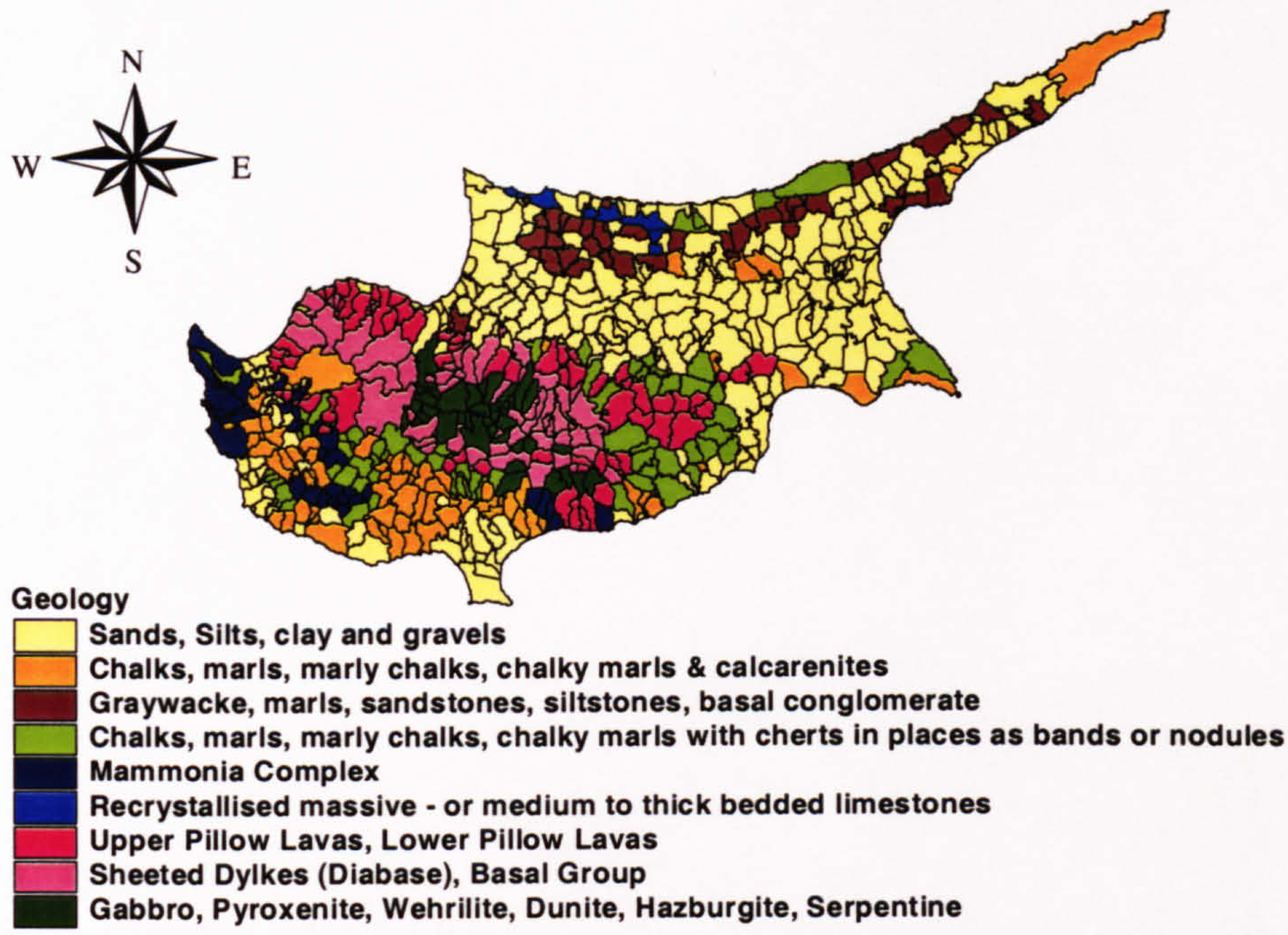


Figure 3.15. Spatial Distribution of the Main geological formations of Cyprus

The values which determine the influence of geology on MMI have been assigned according to Cripps (1999) and based on the values of Table 3.3 given by the New Zealand National Society Earthquake Engineering (1984) (in Cochrane and Schaad, 1992). The selection was mainly based on the age of these geological formations and their characteristics.

Regarding the S value, Theodulidis and Papazachos (1992) classified the geological formations underlying the strong motion recording stations in Greece into three main categories (alluvium [S=0], intermediate hardness [S=0.5], rock [S=1]). This was done according to their hardness as well as based on the Peak Ground Velocity (PGV) / Peak Ground Acceleration (PGA) ratio criteria suggested by Seed et al (1976).

Table 3.3. Subsoil Influence on MMI (NZNSEE, 1984; in Cochrane and Schaad, 1992)

Deep alluvium	+2
High porosity sediment	+1
Compact sediment (assumed average ground)	0
Basement Rock	-1

Table 3.4. Main geological formations of Cyprus

No	Code	Lithology	Formation	Epoch	Period	Influence on MMI	S value
1	H	Sands, silts, clay and gravels	Alluvium-Colluvium	Holocene	QUATERNARY	+2	0
2	Mi-Mu	Chalks, marls, marly chalks, chalky marls and calcarenites	Pakhna	Middle Miocene	NEOGENE	+2	0.75
3	Mm	Graywacke, marls, sandstones, siltstones, basal conglomerate	Kythrea	Middle Miocene	NEOGENE	+1.5	0.5
4	K_{u3}-Ou	Chalks, marls, marly chalks, chalky marls with cherts in places as bands or nodules	Lefkara	Oligocene Eocene Palaeogene	PALAEOGENE	+1	0.5
5	Ku Tm-Km	Mammonia Complex	Agia Varvara Agios Photios Group Dhiarizos Group	Upper (Maastrichtian) Middle	CRETACEOUS TRIASSIC	-1	0
6	Jl-Kl	Recrystallised massive or medium to thick bedded limestones	Hilarion		JURASSIC	-1	1
7	Ku UPL LPL BG	Olivine, pillow lavas with occasional sheet flows, dykes and sills altered to zeolite facies	Upper Pillow Lavas Lower Pillow Lavas (Volcanic Sequence)	Upper (Campanian)	CRETACEOUS	-1	1
8	Db	Diabase dykes up to 3m wide, aphyric and clinopyroxene and plagioclase-phyric altered to greenschist facies	Sheeted Dykes (Diabase) (Intrusive Sequence)	Upper (Campanian)	CRETACEOUS	-1	1
9	y δ σ4 σ3 σ2 σ1 σ	Isotropic, uralite, and olivine gabbros, websterites, wehrilites, dunites, tectonized harzburgites, etc.	Gabbro Pyroxenite Wehrilite Dunite Hazburgite Serpentine (Mantke Sequence)	Upper (Campanian)	CRETACEOUS	-1	1

3.2.7 Summary

This section has presented a reanalysis of the historic seismic data for the area of Cyprus. Through linear regression, two relationships were established and used to convert the M_L and m_b magnitudes into M_S. Two recurrence relationship were derived, based on the earthquake catalogue and it was found that a polynomial form of the relationship fitted the observed data (1894–1998) best. However, in this research only the best fit linear recurrence relationship and Ambraseys relationship are examined.

The energy release for the period of 1894 to 1998, associated with each of the events in the historic data series has been calculated, and a plot of cumulative energy release over time was presented. It was observed that periods of intense seismic activity have been separated by tranquil periods, typically twenty-four years in duration. The plot of cumulative seismic energy release produced using the polynomial regression relationship fitted the observed data (1894–1998) very well. On average, the seismic energy release for the area of Cyprus is 4.32×10^{19} ergs per year.

The spatial distribution of released energy was also examined. The distribution could indicate a seismic gap centred on the point 34.2°N, 33.2°E. On the other hand, if the structure of the Cyprian Arc is a double fault or a broad zone of thrusting then the lack of seismic activity in this zone is less significant.

The depth of the earthquakes was examined in an attempt to establish whether there is a dipping seismic zone present. The results of the study proved the existence of a dipping zone. However, its inclination is opposite to that of the subduction zone, which contradicts the theories surrounding earthquake occurrence near island arcs. Furthermore, it was established that shallow earthquakes do occur inland; this increases the potential earthquake risk.

Finally, suitable attenuation equations were selected and it was decided that the effect of geology will be taken into account through modification factors.

3.3 VULNERABILITY

3.3.1. DATA COLLECTION

3.3.1.1. MEAN DAMAGE RATIO (MDR)

One of the main input parameters for the estimation of the earthquake risk is the vulnerability of the building stock of the area under consideration. For the vulnerability to be involved in the calculation of the risk it is necessary to develop a correlation between the earthquake intensity and loss for the building stock in Cyprus. The development of such relationships is a major task. However, Schnabel (1987) based on careful comparison of all the data and information available, and taking into consideration the contrasting building standards in various countries; produced a set of vulnerability curves for the island of Cyprus.

Schnabel (1987) separated the building stock of Cyprus into three main groups, buildings with less than four storeys, buildings with more than 4 storeys, and industrial halls (Table 3.5). A further classification was made based on the quality of the construction, and the building stock was divided into Superior Construction and Standard/Substandard construction (Table 3.5).

Table 3.5. Mean Damage Ratios (MDR) for Cyprus (Schnabel, 1987)

	SUPERIOR CONSTRUCTION					STANDARD / SUBSTANDARD CONSTRUCTION				
	INTENSITY									
Type of Construction	VI	VII	VIII	IX	X	VI	VII	VIII	IX	X
< 4 storeys	0%	5%	11%	25%	40%					
Buildings						8%	17%	36%	75%	100%
> 4 storeys	5%	7.5%	14%	32%	58%					
Industrial Halls	1%	4%	12%	30%	60%					
Factors to be applied on MDR building / hall	0.2	0.25	0.33	0.50	0.67					

Despite the fact that the curves are a subjective interpretation of limited data and, according to Schnabel (1987) they should not be regarded as conservative curves particularly for higher intensities, they still represent the best possible approximation of the actual conditions. Whilst it is appreciated that theoretical loss forecasts are highly unreliable, it was decided to use these curves due to the unavailability of other data which would enable the estimation of the vulnerability of buildings. Some adjustment to the values will be necessary to accommodate the different types of construction. The MDRs adopted for this research can be found in Table 4.14 of section 4.4.2.

3.3.1.2. BUILDING STOCK

Construction and Housing Statistics (1994)

The building stock data, used for the analysis of the vulnerability, were obtained from the Census of Population (1992) published by the Department of Statistics and Research of the Ministry of Finance.

For each village and town area the number of houses (Figure 3.16), based on the year of construction, but not the type of construction (Section 3.1 - Appendix B), is known. The year of construction and the type of construction combined are only given in a more general form based on rural and urban residence (Table B-1 and Table B-2 - Section 3.3 - Appendix B).

According to the Department of Statistics and Research of the Ministry of Finance (1994) the tendency of the Cypriot population to leave their villages and move to the cities has been a major problem for the island, which created large scarcely populated areas and smaller very densely populated areas.

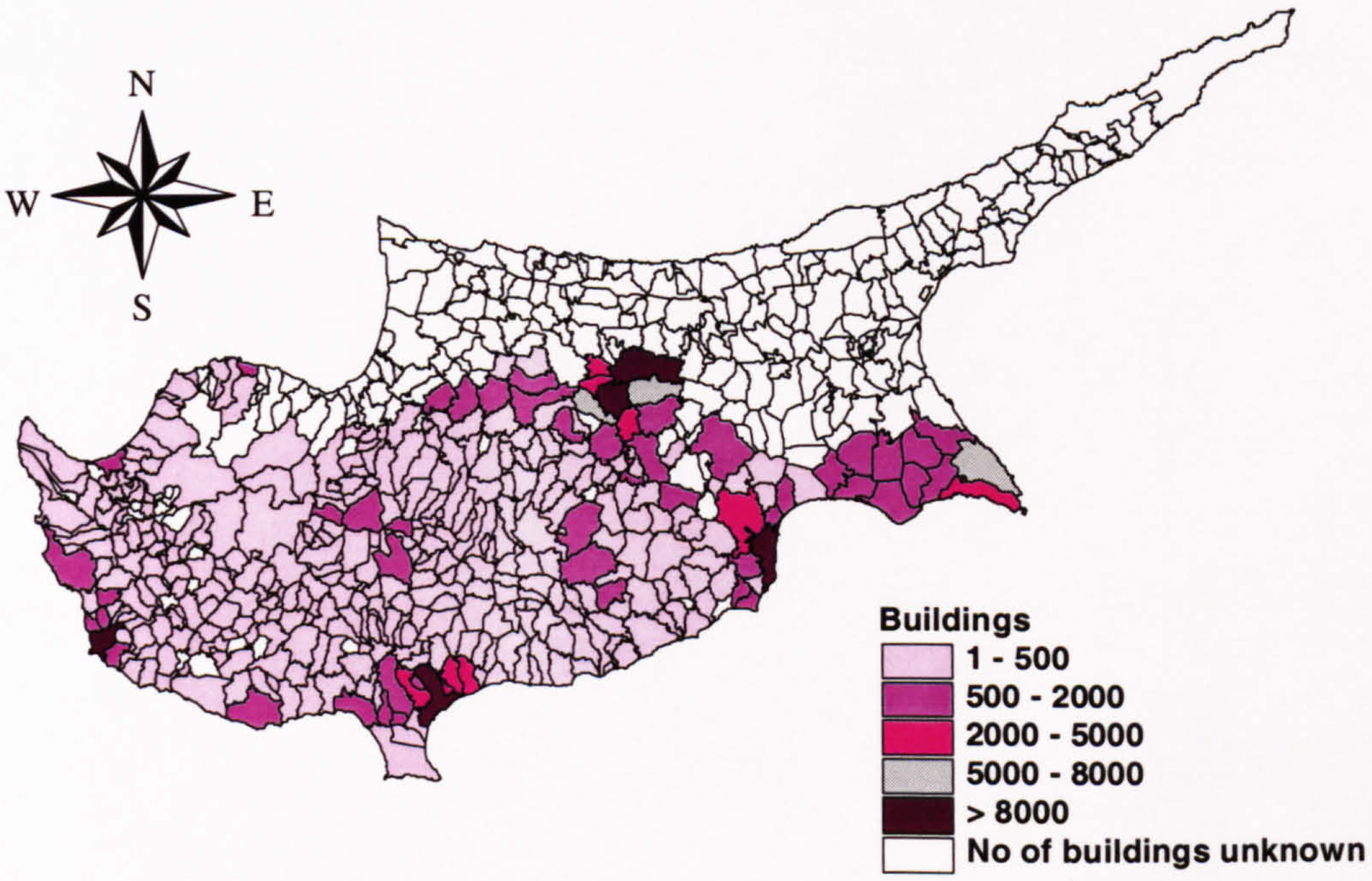


Figure 3.16. Spatial Distribution of the building stock – conventional dwellings of Cyprus

As far as the urban areas are concerned these are defined by the Local Plans and include the municipal area, the suburban area and some villages of the greater urban area. More specifically the urban areas are listed in Table B-8 - Section 3.3 - Appendix B. Based on the assumption that all rural/urban areas have the same proportions (%) of the different types of buildings, it was possible to calculate the percentage of the various types of buildings in each individual village and town (See Table B-9 - Section 3.3 - Appendix B).

In order to be able to use the MDRs it was necessary to assign the various types of conventional dwellings to one of the three categories selected by Schnabel (1987). Since actual data do not exist this allocation was based on the experience of the general building stock of the island (Table 3.6).

Table 3.6. Types of Conventional Dwellings

Buildings with < 4 storeys which will be called low rise buildings	Single Houses
	Semidetached or doublex
	Row Houses
	Backyard Houses
	Not stated
Buildings with > 4 storeys which will be called high rise buildings	Apartment blocks
	In partly residential building
	Other

The year of construction of a particular structure played an important role in its classification as being a superior or standard/substandard construction. Table 3.7 presents the percentages assigned for each quality. These percentages were selected from experience, based on the known construction practice in the island. For instance reinforced concrete structures, which could be classified as superior construction, were first introduced in the 1960s and the aseismic code was introduced in the mid 1980s. For simplicity purposes the buildings with unknown year of construction (Not stated) were equally divided and added to the other periods (decades) of construction. It must be understood that these values were not obtained from any calculations or analysis; rather than simply selected in a way that would characteristically represent the quality of the building stock of the island.

Table 3.7. Assigned percentages of the superior and standard/substandard construction for each time period

Year of construction	Adobe/Stone		RC houses		RC apartments	
	Standard Substandard	Superior	Standard Substandard	Superior	Standard Substandard	Superior
Before1950	100%	0%	80%	20%	50%	50%
1950-1959	80%	20%	60%	40%	40%	60%
1960-1969	60%	40%	50%	50%	30%	70%
1970-1979	40%	60%	40%	60%	35%	65%
1980-1989	0%	0%	10%	90%	10%	90%
1990-1992	0%	0%	0%	100%	0%	100%

The information on the living quarters whatever their type (houses, apartments etc.) is very detailed whereas there is no information on the industrial halls, dams, roads, hospitals etc. in the Construction and Housing statistics (1994). The number of some establishments in each village and town are known. These are separated based on the branch of economic activity they belong. The various branches are given in Table 3.8.

There is no information regarding their type of construction; nevertheless, it was decided that for a realistic representation of the building stock of Cyprus they would be divided into three categories adobe, RC < 4 storeys and RC > 4 storeys, based on the building type distribution of the living quarters. Furthermore, the establishments were divided into public and private (Table 3.8). Whilst the private establishments follow the same MDR for each different type of building the public are considered to have a lower vulnerability and they are therefore allocated the MDR of RC > 4 storeys which is the lowest used.

Table 3.8. Public/Private Establishments

Type	Category
Mining, Quarrying	Public
Manufacturing	Private
Electricity, Gas, Water	Public
Construction	Private
Trade	Private
Restaurants	Private
Transport, Communication	Public
Financing, Insurance	Private
Services*	Public

* *Medical, Education, Public Administration, Hairdressers, Beauticians, Photographers etc*

In order for the model to be more representative of the building stock of Cyprus, other Ministries were contacted and information regarding the Hospitals, Airports, Power Plants and Dams was obtained. The costs and number of these establishments is well documented. However, it was not possible to obtain information regarding their vulnerability. These structures will be considered to be of superior construction. The lowest MDRs used in this study (i.e. > 4 storeys) are to be used for these establishments.

These data and assumptions were used in conjunction with the data obtained for the values of the buildings (see section 3.4.1 Construction and Housing Statistics 1994) to predict the possible damage costs due to earthquakes of specified magnitude. The results of this analysis are given in chapter 6.

As the research progressed it was possible to obtain further data as far as the building stock is concerned. The study performed by KORONIDA-Centre of Research and Development (Hatjiloizi, 1998) provided a better and more representative set of information of the Cyprus building stock. These new input data were also used for the analysis of the vulnerability.

Data from KORONIDA

KORONIDA presented and evaluated the available information regarding the buildings in the part of Cyprus accessible by the Republic authorities. The data for this study were obtained from the Construction and Housing Statistics (1990 until 1996), from the Census of Population (1992), as well as the Census of Residential buildings (1982), all publications of the Department of Statistics and Research of the Ministry of Finance.

From the study it was identified that residential units comprise 70% of the total cost that are constructed in Cyprus in the private sector. A considerable finding of the study is that there is no major increase in the cost of construction due to the introduction of the aseismic design in 1992. It was recognised that the cost of construction is affected and increased due to the increase in the labour rather than material costs. The study involves only the residential buildings since it was not possible to obtain enough information regarding non-residential buildings such as offices, hotels, or constructions made of steel.

The author attempted to obtain such information and faced the same difficulties. As mentioned before, though, some information regarding non-residential buildings was successfully obtained.

All the assumptions made by KORONIDA as well as their conclusions are presented in Section 3.4 of Appendix B. In addition to these, further assumptions made by the author are included in the same Appendix. These were used to create a new database, which was based on the number of buildings for each village and town obtained from the Construction and Housing Statistics (1994), but separated the buildings into three types, adobe and stone, reinforced concrete houses and reinforced concrete apartments.

3.3.2. DISCUSSION

The vulnerability of the building stock of Cyprus was addressed in this section and whilst it is appreciated that the path followed (i.e. the use of the mean damage ratios) is a crude way of approaching this aspect, it was necessitated due to the lack of adequate data.

For the vulnerability of the buildings to be representative of reality a vast range of building parameters are required. The most commonly used parameters are age, building height, insured value, regularity and symmetry, building use, building quality (base shear), subsoil, and type of construction material (Cochrane and Schaad, 1992).

Unfortunately, for the case of Cyprus such data are unavailable and therefore the use of Schnabels' loss degree curves was unavoidable. It is accepted that the way in which the vulnerability has been approached has its limitations, and future work needs to be done in this field. Nevertheless it will not be considered as a major problem towards the development of the model since the aim is not to develop a detailed model but a model capable of dealing, predicting and suggesting solutions and management strategies.

Verification studies showed that despite the use of such crude mean damage ratios, relatively accurate damages were predicted. Once the appropriate information becomes available it can be included in the model and better predictions should be expected.

3.4 VALUE OF ELEMENTS AT RISK

3.4.1 DATA COLLECTION

Construction and Housing Statistics (1994)

In an attempt to produce a realistic model and in the absence of actual values, it is necessary to use numbers and values as near to the actual ones as possible. Since the value of the building stock of Cyprus is not completely documented it was obligatory to make some simple but essential calculations, in an attempt to obtain appropriate values for the buildings involved in this study. As mentioned before, the information on the living quarters is very detailed and by combining various tables of the Construction and Housing statistics (1994) it was possible to estimate the approximate value of a building in both rural and urban areas.

The process was based on the knowledge of the annual completion and cost of new construction and of the annual total dwelling stock and occupied living quarters. These are summarised in Table 3.9 and Table 3.10. From a simple calculation it was possible to estimate that in general an average building would cost approximately £32000 CY (1994 prices).

Table 3.9. Total dwelling stock and occupied living quarters 1992 (Department of Statistics, 1994)

	Total dwelling stock and occupied living quarters 1992	Built between 1990-1992
TOTAL	231930	22661
URBAN	148567	15066
RURAL	83363	7595

Table 3.10. Completion of new construction of dwellings (Department of Statistics, 1994)

	Output Flow of new construction of dwellings
1990	£218,720,000 CY
1991	£246,441,000 CY
1992	£259,380,000 CY
TOTAL	£724,541,000 CY

Note: At constant 1994 prices

Once more the study of KORONIDA provided further data which were used in an attempt to have the value of elements at risk represented better in the calculations of risk.

KORONIDA Ltd Centre of Research and Development

The study performed by KORONIDA as far as the value of elements at risk is concerned arrived at two main conclusions. The 1974 Turkish invasion and occupation of the 36% of the North part of the island created a high demand of cheap housing for the refugees. Table B-5 in Appendix B shows that for the period 1974 – 1982 most of the residential units constructed had a relative low cost of construction (£5000 to £10000 CY, constant 1982 prices). The average cost of RC, adobe and stone buildings will be calculated in 1996 prices and will be used for the buildings constructed during that period.

The second conclusion concerns the RC houses and apartments. Table B-6 in Appendix B presents the prices from 1990-1996 for the houses and apartments for each town. It is apparent that both the houses and apartments are more expensive in the district of Nicosia and least expensive in Famagusta.

To achieve the best possible representation of the building values in the risk assessment model it was decided that the prices given by KORONIDA would be adopted since they are more realistic, rather than the initial general estimation-assumption of £32000 CY for all the buildings. Some assumptions were necessary due to the lack of complete data. These have been listed in Section 3.4 and 3.5 of Appendix B. From the house prices a £20000 was subtracted to count for the land cost.

Due to the unavailability of any relevant information regarding the costs of the public/private establishments it was decided that these will be assumed equal to the prices that are used for the RC houses. For each different district the corresponding values are to be used. The values adopted for the cost of the living quarters and establishments for this research can be found in Table 4.15 of section 4.4.2.

As mentioned in section 3.3.1.2. the information regarding the costs and numbers of the Hospitals, Airports, Power Plants, Dams is well documented. As far as the hotels are concerned some assumptions were required for their inclusion in the model. All the information regarding these buildings is included in Appendix E (CD-ROM).

3.4.2. DISCUSSION

Various simplifications were necessary when dealing with the cost of the building stock, due to the limited available information. If and when a better database is available it can be employed for a more realistic result. A verification of these simplifications will be undertaken when the estimates of damage are made in section 4.4.2.

3.5 FATALITIES AND INJURIES

3.5.1 INTRODUCTION

The most severe repercussion of earthquakes is the potential enormous loss of human life. The risk to life due to earthquakes is widespread. According to Coburn and Spence (1991) at least 75 countries suffered such loss of life this century. The number of fatalities in Cyprus from 1900-1990 due to earthquakes comes to a total of 40 giving the island a ranking of 52 in the Worlds earthquake countries (Coburn and Spence, 1992). It must be noted that this was the result of a single event (Section 4.1 - Appendix B).

Coburn and Spence (1992) stated and it is widely accepted that the primary focus of most earthquake protection programmes is to save life. For the assessment of the earthquake risk to be complete it must include an assessment of the probable levels of human casualties, both deaths and injuries resulting from an earthquake.

Casualty estimation even though very difficult, mainly due to the highly variable death tolls from one earthquake event to another and also since the data documenting occurrences of life loss in earthquakes are poor, should be performed as part of the loss estimation studies.

The loss of life during an earthquake is caused in many different ways such as:

- Building collapse or collapse of building components or contents
- Machinery accidents occurring during the disturbance
- Medical conditions induced by the shock of experiencing ground motion (i.e. heart attacks)

In addition to these, some earthquakes trigger follow-on hazards, such as rockfalls, landslides, mudflows, tsunamis and fires, which create further loss of life. Furthermore, epidemics among the homeless or even shootings during martial law are also included in the list of life-loss hazards. However, the main cause of fatalities due to earthquakes is structural failure or partial collapse.

On the other hand, in cases where higher quality of building stock is involved (low vulnerability), such as in the USA or Japan, the biggest numbers of fatalities are caused by the failure of non-structural elements (i.e. dislodged pieces from the exterior of buildings, collapse of free standing walls). Earthquake induced accidents are also to blame. Coburn and Spence (1992) examined the causes of the earthquake fatalities and these are presented in Figure 3.17.

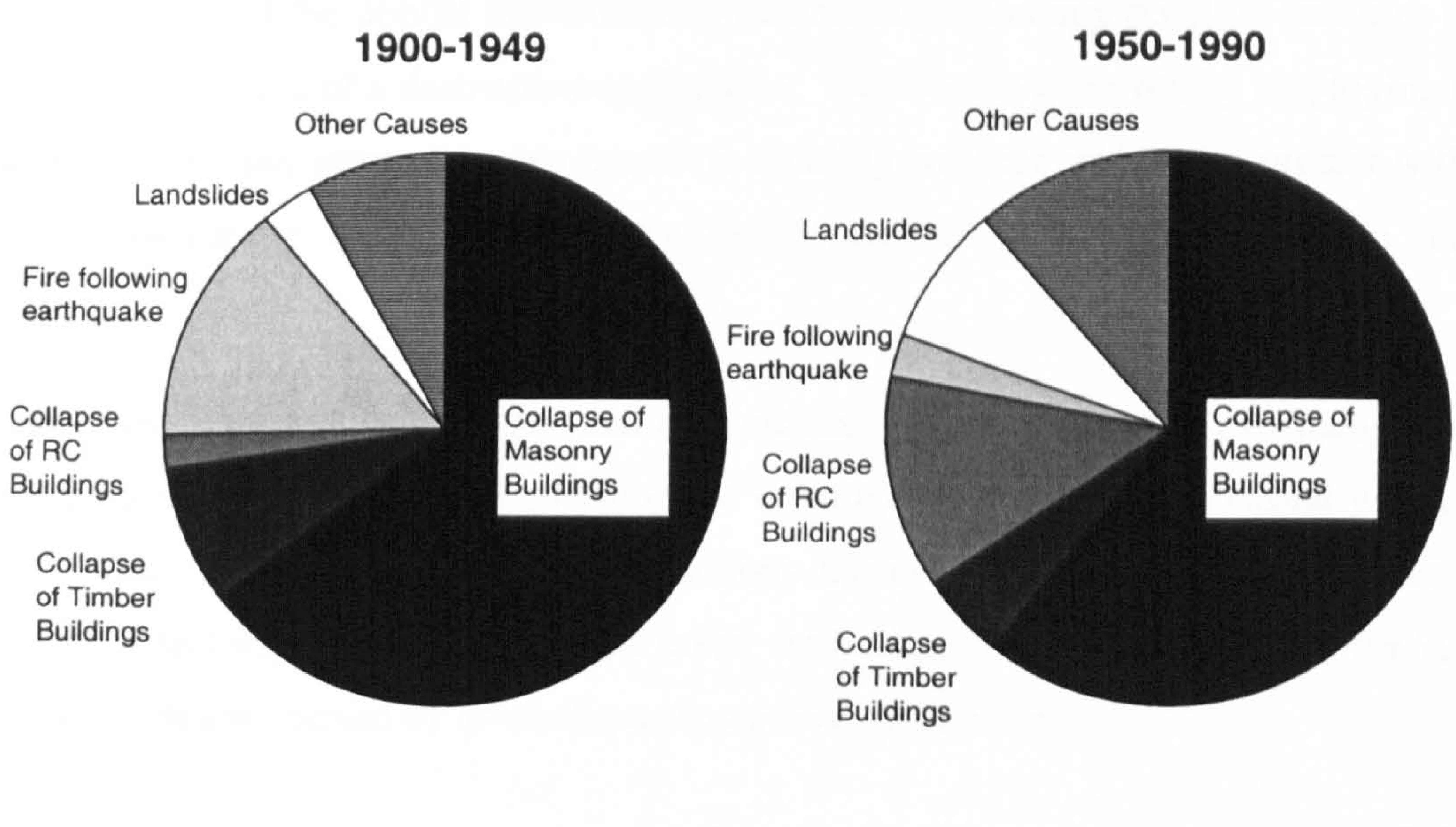


Figure 3.17. Breakdown of fatalities attributed to earthquake by cause for each half of this century (after Coburn and Spence, 1992)

From Figure 3.17 it can be seen that about 60% - 65% of earthquake fatalities are caused by the collapse of masonry buildings, mainly adobe, rubble stone, rammed earth or unreinforced brick and concrete block masonry. As far as the concrete framed houses are concerned they are considered safer and therefore less likely to collapse. However, they are also vulnerable and when they do collapse they are more deadly and kill more of their occupants than masonry buildings.

3.5.2 HUMAN CASUALTY ESTIMATION

By examining the total number of people killed against the total number of buildings heavily damaged, for earthquakes where both statistics were known, Coburn and Spence (1992) were able to identify that deaths are broadly related to the destruction caused by earthquakes. Based on the causes of fatalities they were also able to separate the earthquakes into two categories. The ones resulting in fewer than 5000 damaged buildings and those with more than 5000 damaged buildings. In the first category a lot of the fatalities and injuries are caused by damage to non-structural elements, various accidents etc. therefore they are quite unpredictable. Whereas with earthquakes with more than 5000 damaged buildings (i.e. more destructive earthquakes) the causes of deaths and injuries mentioned above, also occur, but the majority of fatalities are due to building collapse.

In most earthquake prone areas the highest risk arises from the highly destructive earthquakes. Furthermore, these are the main focus of concern in earthquake protection measures. It is of the utmost importance to be able to predict any possible fatalities and injuries in the event of a destructive earthquake. This can be achieved by employing the use of casualty occurrence models based on building collapse which can predict within certain confidence limits, the casualty totals (i.e. fatalities and injuries) in large earthquakes.

Coburn and Spence (1992) suggest that the available data as well as the intended uses of the output should be the ones governing the complexity of any human casualty model. Furthermore, in all future casualty predictions the errors associated with the current prediction techniques must always be taken into consideration. In general, the total number of deaths caused by an earthquake can be expressed as:

$$K = K_S + K' + K_2 \tag{3.7}$$

where: K_S is the number of fatalities due to structural damage

K′ is the number of fatalities due to non-structural damage

K_2 is the number of fatalities arising to follow –on hazards (rockfalls, landslides, mudflows, tsunamis, fires)

Table 3.11 presents the various characteristics of the three casualty variables involved in the prediction of the total number of casualties resulting from an earthquake.

Table 3.11. Characteristic of the casualty equations' variables

Variable	Cause	Comment
K_S	structural damage	Consistent, controlling factor for most large and destructive earthquakes, contributes a large percentage of the total deaths from earthquakes.
K′	non-structural damage	Dominant at low levels of damage, highly variable and difficult to predict
K_2	follow –on hazards	rare but when it occurs it is likely to dominate the total

As it can be seen the only variable able to be "efficiently" and "adequately" predicted is K_S. The development of a model for this variable (K_S) can be assessed from the following methodology.

3.5.2.1 Lethality Ratio

According to Coburn and Spence (1992) the lethality ratio is the required parameter and is basically the relationship between the number of people killed and the number of collapsed buildings. If this ratio is known, then from the estimates of the collapsed buildings it is possible to estimate the human casualties.

The casualty model is the separate serial application of the various factors (M1 to M5) to each different class of buildings (depending on the type of construction, quality of construction, etc). The addition of the number of fatalities caused by the damages/collapses of all the different building types affected by the particular earthquake give the total fatalities. Equation 3.8 expresses the number of fatalities, resulting from the damage caused to the specific class "b" buildings.

$$K_{S_b} = D5_b \times [M1 \times M2 \times M3 \times (M4 + M5(1 - M4))] \quad (3.8)$$

where: $D5_b$ is the total number of collapsed structures (damage level 5 i.e. for load-bearing masonry - more than one wall collapsed or more than half of roof, for RC framed buildings – failure of structural members to allow fall of roof or slab) of buildings of type b

M1 to M5 are a range of modifiers to a potential mortality figure

Table 3.12 presents the description for the various factors required for the estimation of the earthquake fatalities.

Table 3.12. Description for the various modifiers to a potential mortality figure

Factor	Description
M1	Population per Building
M2	Occupancy at time of earthquake
M3	Occupants trapped by collapse
M4	Injury Distribution at collapse (T_0)
M5	Mortality post-collapse

Coburn and Spence (1992) suggested ways of calculating the factors influencing the lethality ratio and these are given in Section 4.2 of Appendix B.

3.5.2.2 DISCUSSION

The Coburn and Spence (1992) process for the estimation of the lethality ratio although very thorough and comprehensive is not ideal for the purposes of this research. The reason being the lack of adequate data which has necessitated the implementation of a simpler way of establishing the specific ratios for the estimation of the fatalities and injuries. The following sections will explain better the considerations made for the special case of Cyprus.

3.5.3 EARTHQUAKE LIFE LOSSES IN CYPRUS

Currently the number of fatalities in Cyprus since 1896, due to both primary and secondary effects of earthquakes, comes to a total of 44 and the number of reported injuries to 282 (Table 3.13).

Table 3.13. Fatalities and Injuries in Cyprus due to earthquakes since 1896

Date	Time of occurrence			M_S	Fatalities	Injuries
	Hrs	Min	Sec			
20th January 1941	03	37	00	5.9	-	24
10th September 1953	06	05	00	6.0	40	150
15th September 1961	01	46	10	5.7	-	2
23rd February 1995	21	03	04	5.7	2	21
9th October 1996	13	10	52	6.5	2	85
				Total	**44**	**282**

Many factors have influenced the outcome of these events. In the following paragraphs an attempt is made to explain and justify the most important of these factors.

The time of occurrence always influences the fatality and injury numbers. The epicentre of an earthquake is also of great importance, luckily up to now the major events have occurred in the sea.

The most seismically active area of Cyprus is the southwest coast of the island. This is a mainly rural area (agricultural) and most of the people there are farmers and shepherds, though this area is rapidly developing its tourism. Depending on the season (weather) they would either be outdoors working in the fields from dusk till dawn or indoors.

The villages of Cyprus and particularly the ones in the Paphos district have always been suffering from declining or out-migration of population. This created low levels of P/B ratios (Population/Building), which are maintained rather constant during the winter months. However, during the summer period due to the massive influx of tourists, the population of these areas increases significantly and in some cases it doubles or even triples.

In general by examining the map of Cyprus one could be influenced to think that the island is densely populated mainly since the average distance between any two villages is less than 10km. However, due to the low village population, Cyprus is not so densely populated (Figure 3.18). Therefore, there was never a need to build vast numbers of high-rise buildings to house the islanders. High-rise buildings are mainly restricted to the urban areas.

Ambraseys (1963) identified that most of the populated areas in the island appear to be situated on geological formations that would in general tend to intensify seismic hazard (i.e. Nicosia – alluvial plain on Miocene marls, Famagusta, Larnaka, Limassol, Paphos – on the shore partly on alluvium). During the last century the towns of Cyprus (despite being affected by many earthquakes) did not sustain devastating damage. Nevertheless, historical evidence shows that many ancient cities were destroyed by earthquakes.

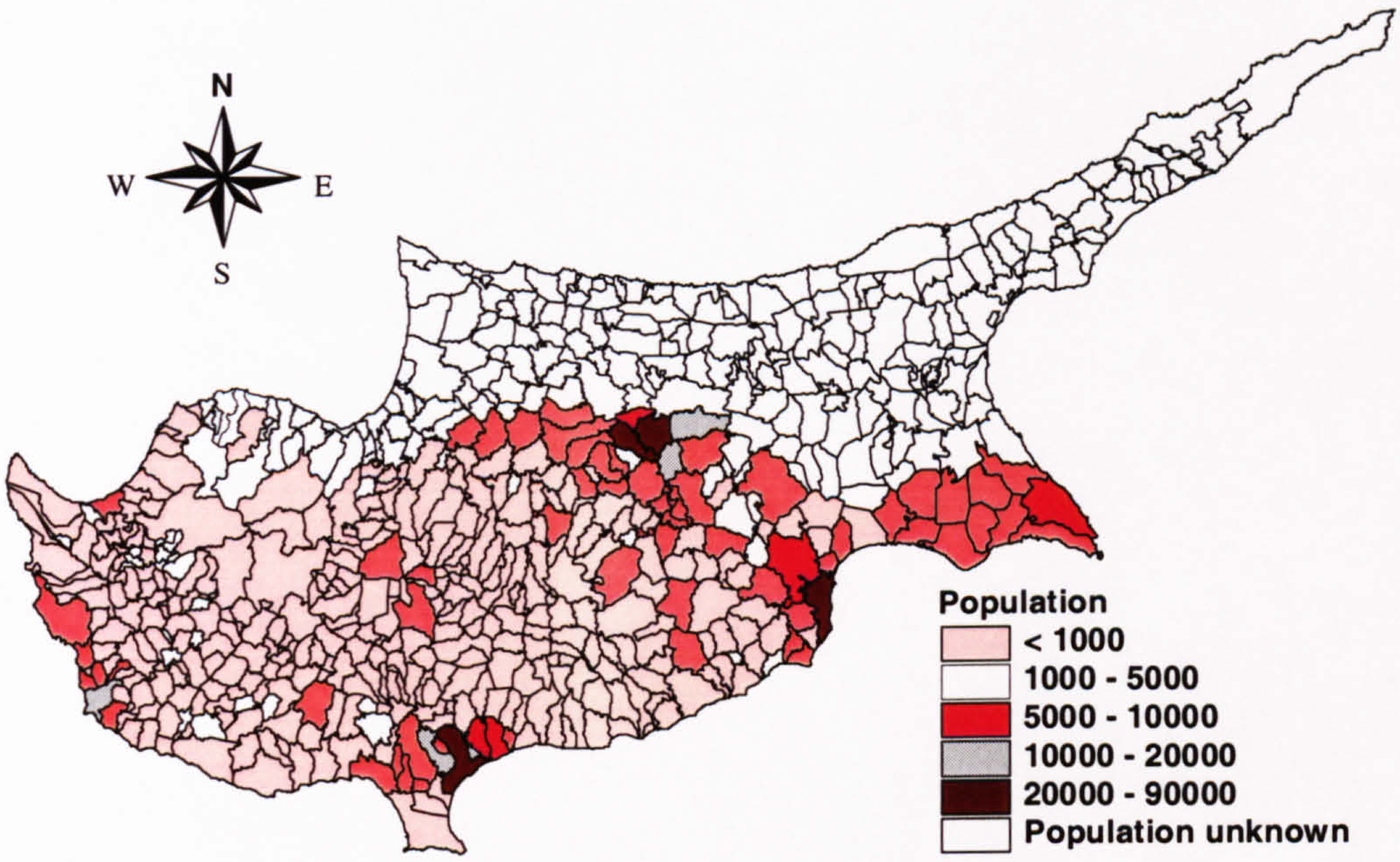


Figure 3.18. Population Distribution

From the information presented it is obvious that there are not enough data to enable the estimation and application of an individual lethality ratio. Similar values to the ones obtained from studies of other areas with similar infrastructure which experienced many fatalities and injuries (i.e. Turkey, Italy, Greece etc) will be used. Studies performed by Nunez (2000) and Cella et al. (1998) have been obtained and the most relevant information is presented in the following section.

3.5.3.1 Casualties Vs Damaged Buildings

A. Izmit – Turkey

Nunez (2000) reporting on the 1999 Izmit Turkey earthquake identified a strong correlation of increasing casualties (fatalities and injuries) with increasing number of buildings damaged. By plotting these data against the data from thirteen other events that occurred between 1914 and 1998 in Turkey (Figure 3.19), he showed that this correlation is consistent.

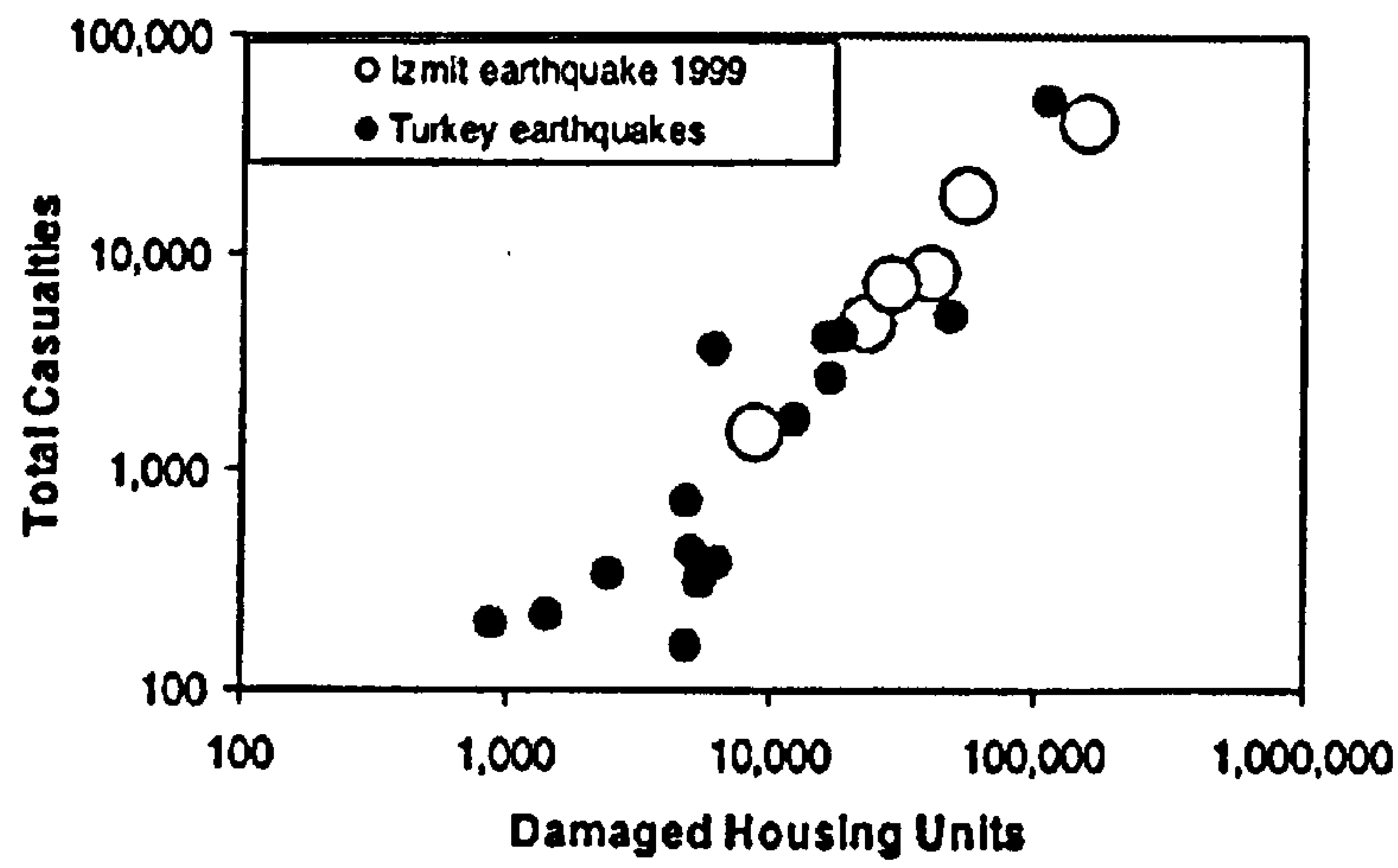


Figure 3.19. Increase in total casualties with total damaged housing units, from the Izmit event (aggregated by province and total) and from 13 other earthquakes in Turkey from 1914 to 1998 (after Nunez, 2000)

The 1999 Izmit earthquake resulted in a massive structural destruction with an even greater loss of life. The outcomes of this event have been summarised in Table 3.14.

Table 3.14. Structural and Human Losses from the 1999 Izmit Turkey earthquake

Structural Losses	Destroyed	60,434
	Moderately Damaged	58,860
	Lightly Damaged	68,391
Human Losses	Dead	15,363
	Injured	23,893

From a simple calculation it was possible to estimate the average ratios of collapsed buildings/fatalities and collapsed buildings/injuries to be respectively equal to 3.9 and 2.5. In other words there were approximately 3 fatalities and 4 injuries in every 10 collapses.

According to Nunez (2000) tremendous reductions in fatalities are possible if the buildings are less vulnerable and hence sustain less damage. This is illustrated by the Loma Prieta, California, USA (M 7.1), and Northridge, California, USA (M 6.7) as well as Chi-Chi, Taiwan (M 7.6) earthquakes. Less than 80 people were killed by either one of the first two events, whereas the third one caused 2400 fatalities. From Nunez (2000) analysis, it is concluded that by an increase of 20% to 50% of the proportion of good buildings, the number of fatalities and also of total injuries would be reduced respectively by around 35% to 75% and 20% to 50%. Nunez (2000) proposes that an improvement to the RC buildings in Turkey to the levels of the ones in California and Japan would save over 95% of potential fatalities.

Even though these values might not be easily applicable for the particular case under consideration, due to the great difference between the building vulnerability of Turkey and Cyprus, they demonstrate the effect vulnerable buildings have to the earthquake protection of the population.

B. TUSCANY - ITALY

Cella et al. (1998) studied the seismicity of the Tuscany Region in Italy (Figure 3.20) and according to them with the vulnerability, hazard distribution, number of buildings and number of occupants known it is possible to estimate the three parameters (units of measure) used to describe the level of damage.

Figure 3.20. Tuscany Region

By applying some simple assumptions the estimated number of collapsed buildings can be used to determine the number of victims (fatalities). The first hypothesis used by Cella et al. (1998) is that fatalities are only provoked by collapsing buildings and that all people staying inside collapsing houses would be killed, unless there was a foreshock, which warned them of the impending danger, and the houses were evacuated. A second hypothesis regarded the estimation of the injured. A correlation of different degrees of damage to buildings prior to collapse, to a typology of injury (i.e. degrees of injuries) was possible from the epidemiological data provided by various recent earthquake events. Cella et al. (1998) appreciate the crudeness of these assumptions and conclude that, for the purposes of comprehensive risk assessments, they are satisfactory.

The events with maximum acceleration above a threshold corresponding to the collapse acceleration were used, and the results presented in Table 3.15 regarding the average number of houses expected to collapse and therefore the expected number of victims (fatalities) for the Tuscany Region and its provinces was estimated.

Cella et al. (1998) admit that an improvement either of the hazard assessment model or of the detail of data and quantity of the vulnerability information would increase the accuracy of these results. Furthermore, the fact that this kind of assessment was carried out only on residential buildings without the use of infrastructure, public facilities, monuments and industries, resulted in a much smaller damage than the real one. The value of the buildings was estimated by multiplying their volume by the cost of construction. The estimated damage is therefore a part of this value and is reached only in case of collapse.

Table 3.15. Expected value of the average annual cost of damage, of the average annual number of victims and the average annual number of collapse (after Cella et al, 1998)

TUSCANY REGION								
Districts	District Code	Municipality Number	Volume thousands of m^3	Building Number	Inhabitants Number	Damage (million of liras)	Victims	Collapse
Massa Carr.	45	17	25046.5	50022	198963	583	0.2	0.8
Lucca	46	35	51594.7	105756	374341	1587	0.4	1.3
Pistoia	47	22	83336.5	92870	701585	7760	0.3	0.4
Firenze	48	44	66237.8	105573	516149	3322	0.2	0.5
Livorno	49	20	43801.2	65850	367316	377	0.1	0.1
Pisa	50	39	32251.5	57844	249225	808	0.1	0.2
Arezzo	51	39	68247.6	91805	569790	2413	0.0	0.1
Siena	52	36	31874.3	49025	212631	1091	0.1	0.2
Grosseto	53	28	42309.8	57764	285309	901	0.0	0.0
Prato	100	7	3564.2	7650	18408	222	0.0	0.1
Total		**287**	**448264.0**	**684159**	**3493717**	**19065**	**1.2**	**3.5**

Similarly to the high death and injury tolls experienced in the Turkey collapses, the situation in Italy produced rather high values for collapses to fatalities ratios (i.e. 2.9). Despite the fact that the results regarding Italy represented annual outcomes the high number of fatalities predicted (i.e. in every 10 collapses there will be approximately 3 fatalities) could equal easily the outcome of just a single event (as in the case of Turkey).

3.5.3.2 MEAN FATALITY RATIOS (MFR) & MEAN INJURY RATIOS (MIR)

It is appreciated that the number of collapsed buildings influences the fatality and injury totals. The available earthquake data for the island of Cyprus though, which could be used to relate and estimate a ratio between the collapsed buildings, fatalities and injuries, are limited (earthquakes of 1953, 1995, 1996). It was therefore decided to obtain the necessary percentages suitable for their prediction through the modification of the MDRs used for the prediction of the damaged buildings.

In order though to be able to multiply these MDR with the population, it was necessary to arrange the population distribution in a suitable format (i.e. separate the total population of each village or town between the three present building categories, adobe, RC houses and RC apartments). The population of each village and town is known. Based on the assumption that the percentages for each type of building would be the same for the population, it was possible to multiply these percentages with the specific population of each village or town and calculate the numbers of people living in each category of buildings within that area. If for instance 10% of the buildings in an area are adobe built in the 1960s it was assumed that 10% of the population of that area are living in those adobe buildings.

It must be mentioned that due to the lack of detailed information regarding the work place in contrast to the complete and detailed information regarding the living quarters of the population, the known establishments were assumed to be the only work places available in the island. It was also assumed that the population of the island is basically shifting between home–work-outdoors based on the population presence patterns discussed in chapter 4 (Table 4.10).

As far as the Hospitals, Airports, Power Plants, Dams and Hotels are concerned their population distribution is not straightforward. Since the numbers of beds of the hotels under consideration are known, it will be assumed that these numbers correspond to persons. As far as the hospitals and airports are concerned it is impossible to estimate population figures. It is assumed that the people present in these establishments are therefore not at work or home and in a way they are safer since it is hoped that the vulnerability of these structures is considerably lower than that of the living quarters and work establishments. It is expected that there will be no fatalities and injuries from these structures.

The Power Plants and the Dams are assumed to employ an extremely small number of the islands' population. Any fatalities or injuries in these establishments would be considered as much a loss, as the perish of any other part of the population in any other type of buildings. Perhaps with even more distress since this would mean loosing the plants' operators and therefore loosing the ability to operate these establishments. However, the numbers of the employees are so small that they would impose a great difficulty if their inclusion in the model is attempted.

It was impossible to obtain any information regarding the population of the occupied area of Cyprus. For the purposes of this work, the villages and towns of that area will be considered uninhabited.

3.5.4 CONCLUSIONS

In this section an attempt was made to present the aspects involved in the cause, estimation and reduction of the fatalities and injuries caused by earthquakes.

The various factors, direct and indirect, that are involved with these losses have been presented and a model for the estimation of the earthquake fatalities and injuries was examined and its various parameters analysed.

Furthermore, two separate studies regarding building collapses to fatalities and injuries ratios have been presented and their results are used as guidelines for the proposed fatality and injury ratios applied in the model.

Two specific proposals on how the population distribution within the various building types and the fatality and injury estimation will be included within the ERA model are made.

MODEL DEVELOPMENT & VALIDATION

4.1 INTRODUCTION

This chapter presents the development and validation of the Earthquake Risk Assessment (ERA) model (EQ-RACY: EarthQuake Risk Assessment for Cyprus), and identifies its limitations.

4.2 EQ-RACY MODEL

4.2.1 OUTLINE OF THE MODEL

Figure 4.1 gives the general outline of the EQ-RACY computer simulation model, which is based on the probabilistic ERA method in a 2-D framework. This model relies on a digitised map of Cyprus which includes information on all villages and towns. Each area (V_i) is assigned individual characteristics and its seismic hazard and earthquake risk are assessed separately. The model is divided into three main parts and three different colours are used to make the flow chart easier to follow. The yellow colour denotes a process part of the seismic hazard assessment. Different earthquakes are denoted by the variable j. The green colour indicates the processes involved in the earthquake risk assessment and the orange the ones involved in the estimation of the life losses. Detailed descriptions and flow charts for each individual part of the model are included in the following sections.

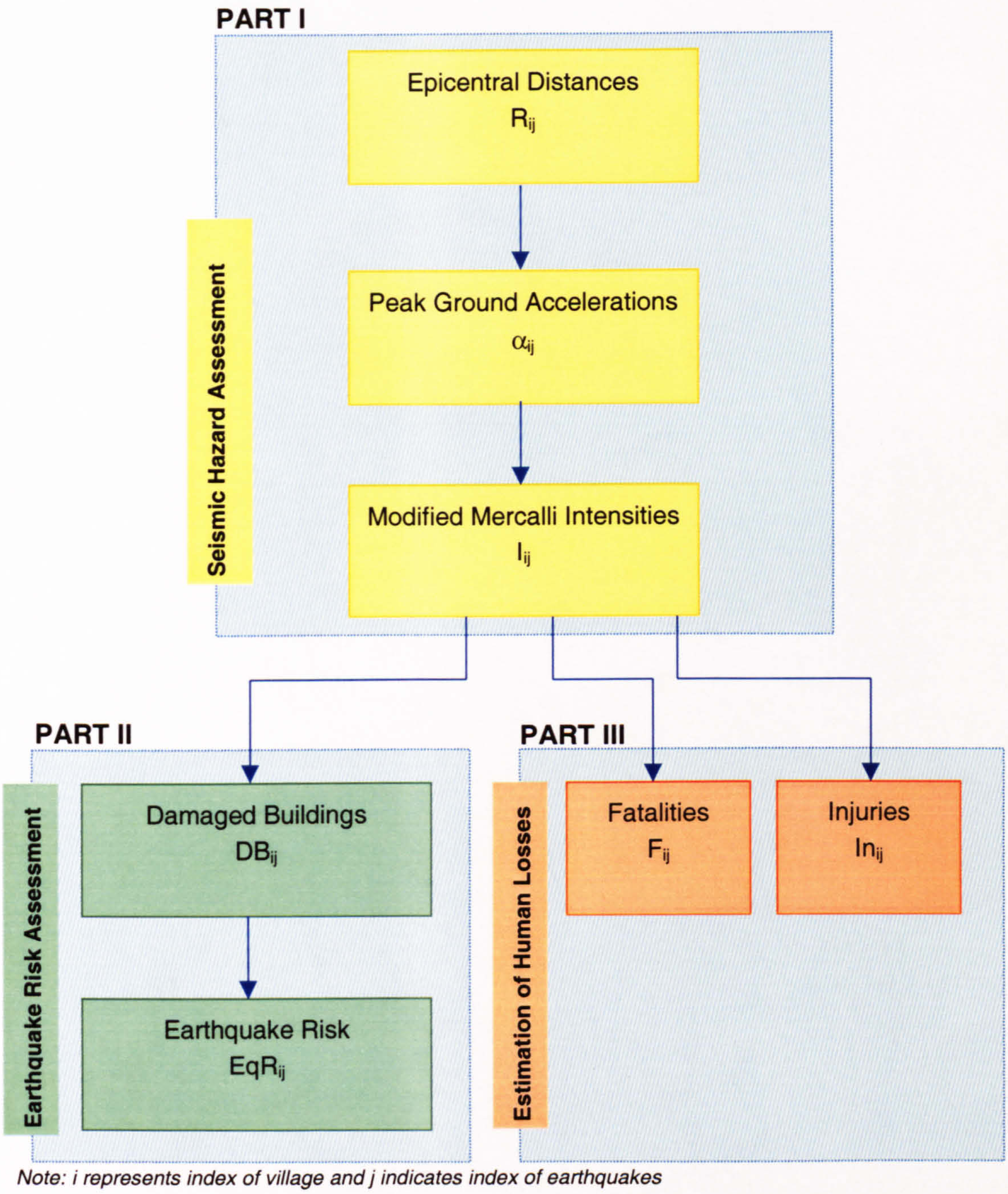


Figure 4.1. General outline of the outputs of the EQ-RACY model

4.2.2 ANALYSIS OF THE PROCESS

All the information pertinent to the decisions to be made was arranged in databases with the administrative codes of each area (V_i) as a common point of reference. All the information included in these databases was either collected from various government departments of the Republic of Cyprus, or prepared based on personal experience or due to lack of data they were assumed to the best knowledge as detailed in chapter 3. The digitised map of Cyprus, with the various administrative areas (i.e. villages and towns) identified, was obtained from the Department of Lands and Survey of Cyprus. For convenience the calculation framework was based around spreadsheets (EXCEL) that allowed the databases to be presented without difficulty and interactions between them to be modelled. The digitised map of the island was entered as input into a GIS (Arc View) package and this enabled the visual presentation of results.

In the following sections an attempt will be made through various tables and figures to explain in detail how the model works from the initial stage of a given earthquake catalogue, to the final spatially distributed end results (i.e. earthquake damages, earthquake risk, fatalities and injuries).

4.2.2.1 PART I – SEISMIC HAZARD ASSESSMENT

Part I of the model deals with the estimation of the seismic hazard. The three input databases of Part I are listed in Table 4.1. The routine starts by calculating the epicentral distance (R_{ij}) for a particular location (V_i) from a particular earthquake (Q_j) (using the Pythagorean theorem) (see Figure 4.2) and then it estimates the peak ground acceleration (α_{ij}) (see Figure 4.3) and finally the intensity (I_{ij}) (see Figure 4.4) through a set of attenuation laws. All equations used are given in Table 4.2.

Table 4.1. Input databases for PART I – Seismic Hazard Assessment

NAME		CHARACTERISTICS
Area Information	V_i	Location of villages and towns
Earthquakes	Q_j	Earthquake catalogue with Year, Month, Day, Hour of occurrence, geographical co-ordinates, depth, magnitude (M_S)
Geology	S_i	The geological type of each area denoted by a number 1 to 9 and the S-value

Table 4.2. Equations used for the Seismic Hazard Assessment

Parameter	Ref	Equation
Epicentral Distances		$R_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$
Accelerations	3a	$\ln(\alpha_{ij}) = 3.88 + 1.12Ms_j - 1.65\ln(R_{ij} + 15) + 0.41S_i + 0.71P$
	3b	$\ln(\alpha_{ij}) = 3.47 + 0.75Mw_j - 0.85\ln Rcer_{ij} + 0.27S_i + 0.66P$
Intensities	3.6	$\ln(\alpha_{ij}) = 0.28 + 0.67\,\mathrm{Im}\,m_{ij} + 0.42S_i + 0.59P$
Hypocentral Distance		$Rcer_{ij} = \sqrt{(R_{ij}^{\ 2} + d_j^{\ 2})}$
Mw		For $4.2 \le Ms_j \le 6.0$ $\quad Mw_j = 0.56Ms_j + 2.66$
		For $6.0 \le Ms_j \le 8.0$ $\quad Mw_j = Ms_j$

Calculation of Epicentral Distances

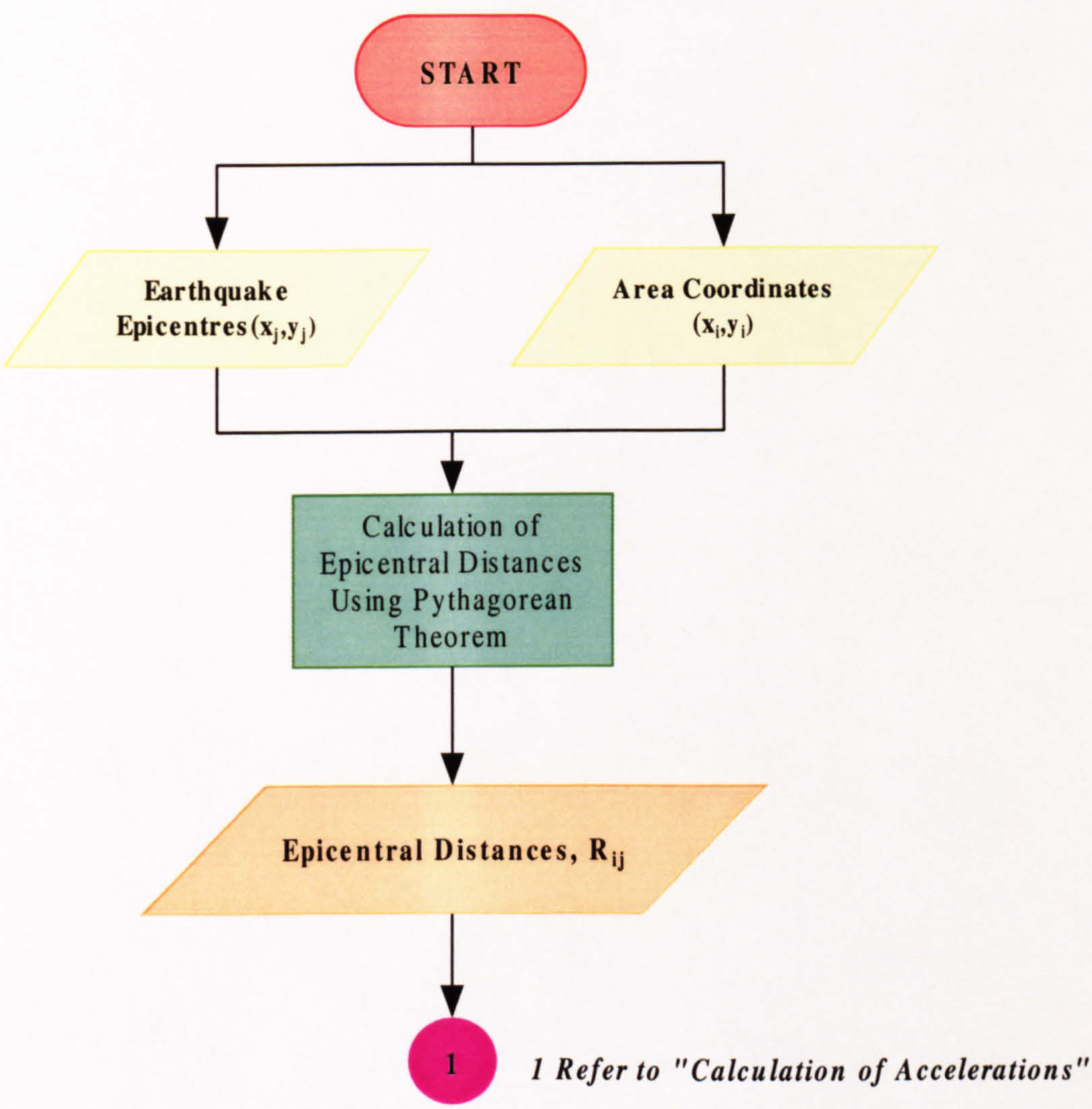


Figure 4.2. Routine for computer simulation Part Ia "Seismic Hazard Assessment - Calculation of Epicentral Distances"

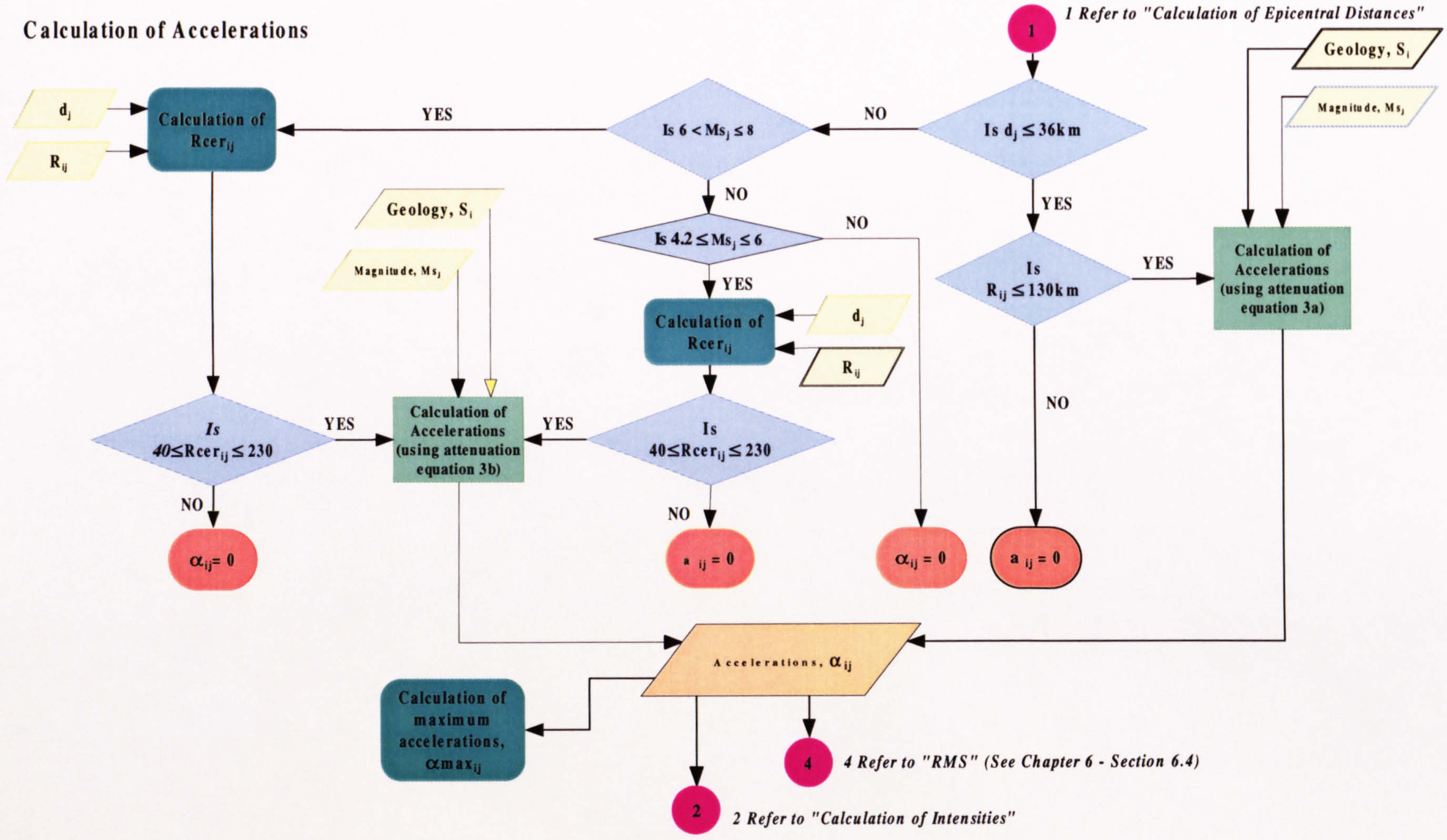


Figure 4.3. Routine for computer simulation Part Ib "Seismic Hazard Assessment - Calculation of Accelerations"

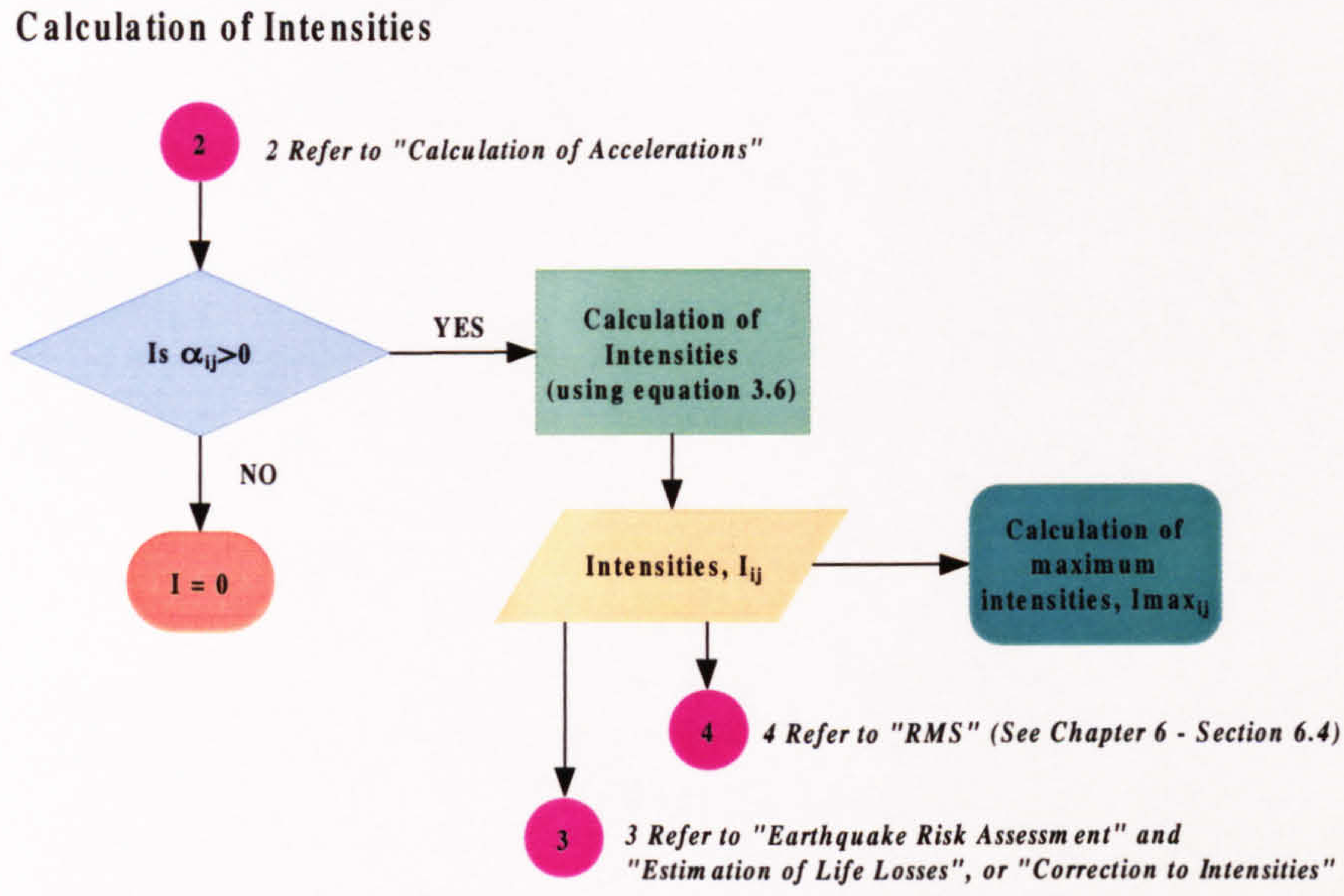


Figure 4.4. Routine for computer simulation Part Ic "Seismic Hazard Assessment - Calculation of Intensities"

It is possible at this stage to prepare the maps for the three output parameters for any particular earthquake as shown in Figure 4.5. It is also possible to identify and present spatially the maximum and average accelerations and intensities experienced in each area when dealing with a series of earthquakes.

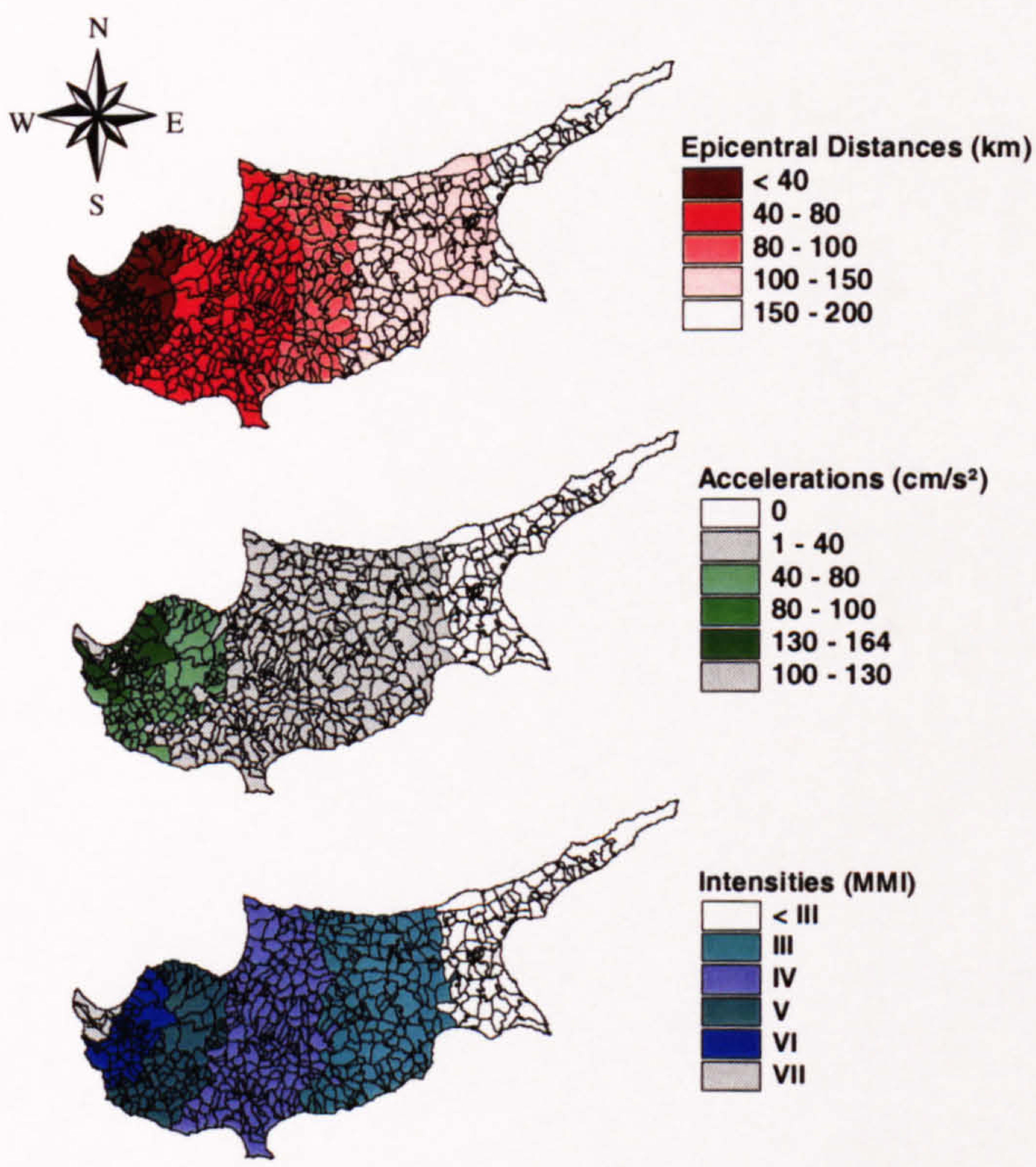


Figure 4.5. Calculation of the epicentral distances, accelerations and intensities caused by the earthquake which occurred on the 23rd of February 1995 with M_S = 5.7 using Theodulidis and Papazachos (1992) attenuation equations

4.2.2.2 PART II – EARTHQUAKE RISK ASSESSMENT

Part II of the model involves the ERA. By checking all individual intensities (for each earthquake) greater or equal to V the model uses the vulnerability models to calculate damage. If the intensity for a particular location and event is less than V, the model terminates the process, since low intensities do not cause any significant damages. The databases required for this part are presented in Table 4.3. The routine is presented in Figure 4.6.

Table 4.3. Input databases for PART II – Earthquake Risk Assessment

NAME		CHARACTERISTICS
MDR	MDR_{ijk}	Mean Damage Ratios for each intensity and each type of building
Building Distribution	B_{ik}	Number of different types of buildings in each area (i.e. village or town)
Value of Buildings	C_{ik}	Value of different types of buildings in each district

*Different types of buildings are denoted by the variable k

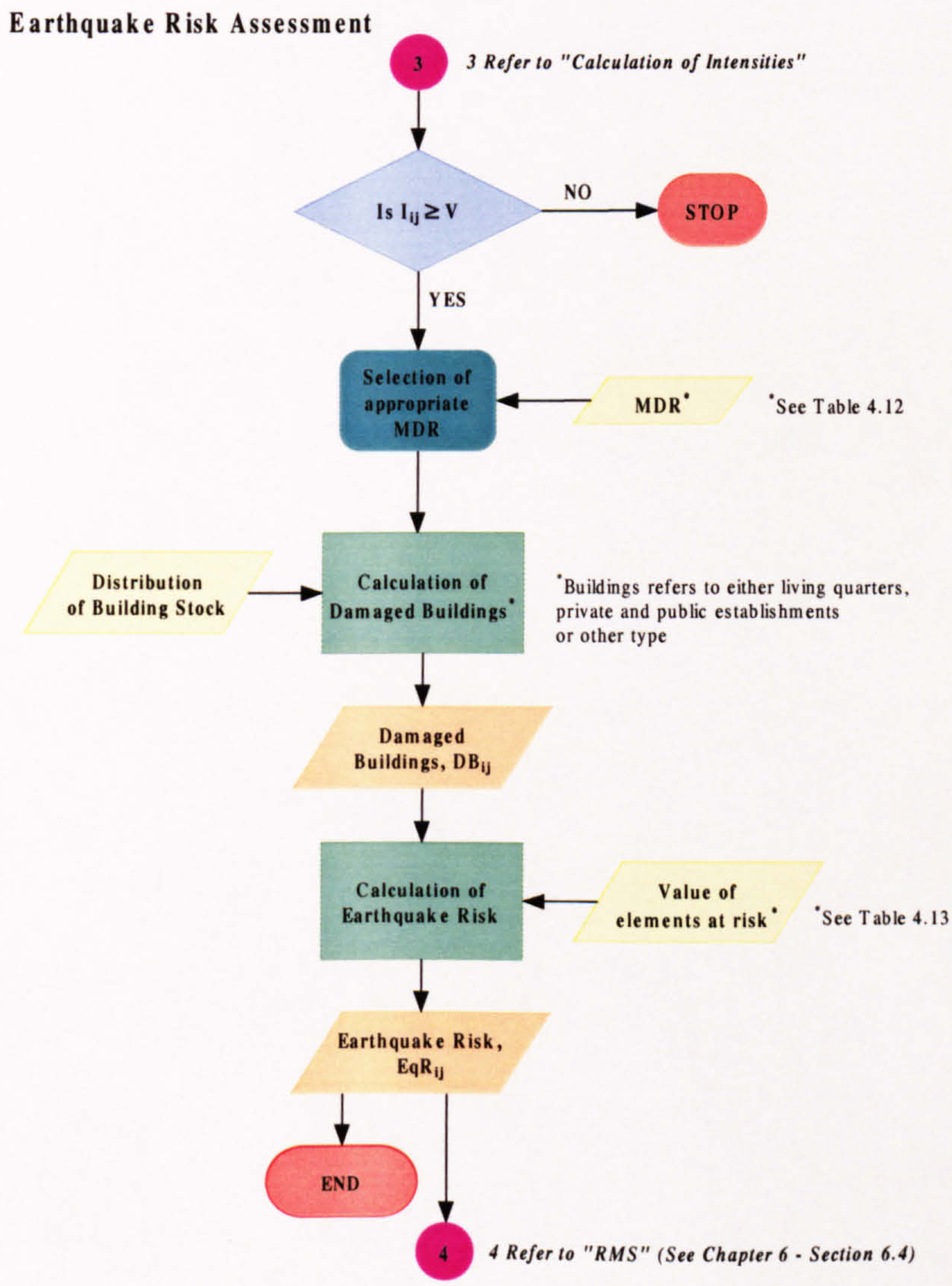


Figure 4.6. Routine for computer simulation Part II "Earthquake Risk Assessment"

Based on the intensity determined for each village and town the appropriate damage ratio is selected for each different type of building and the total number of damaged buildings for each type is calculated (MDR x number of buildings). Once the number of the total damaged buildings is found, (typical results shown in Figure 4.7) the total damage cost is estimated. The monetary values of each type of building (Adobe/Stone, RC House or RC apartment) for each district were determined based on the available statistical information and they are multiplied by the number of damaged buildings to arrive at the earthquake risk (typical results shown in Figure 4.8).

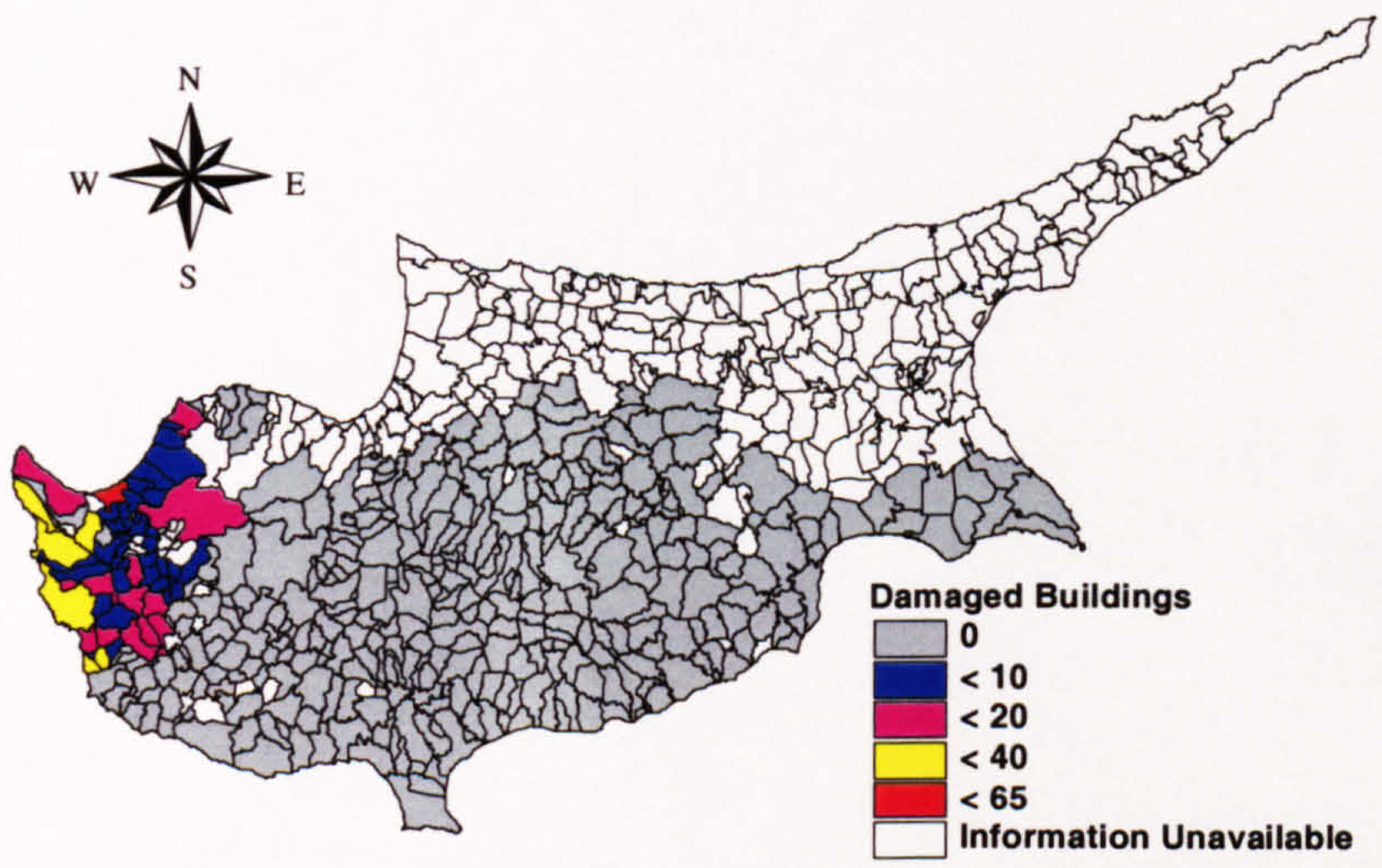


Figure 4.7. Predicted Damaged Buildings with 100% damages as a result of the earthquake which occurred on the 23rd of February 1995 with $M_S = 5.7$

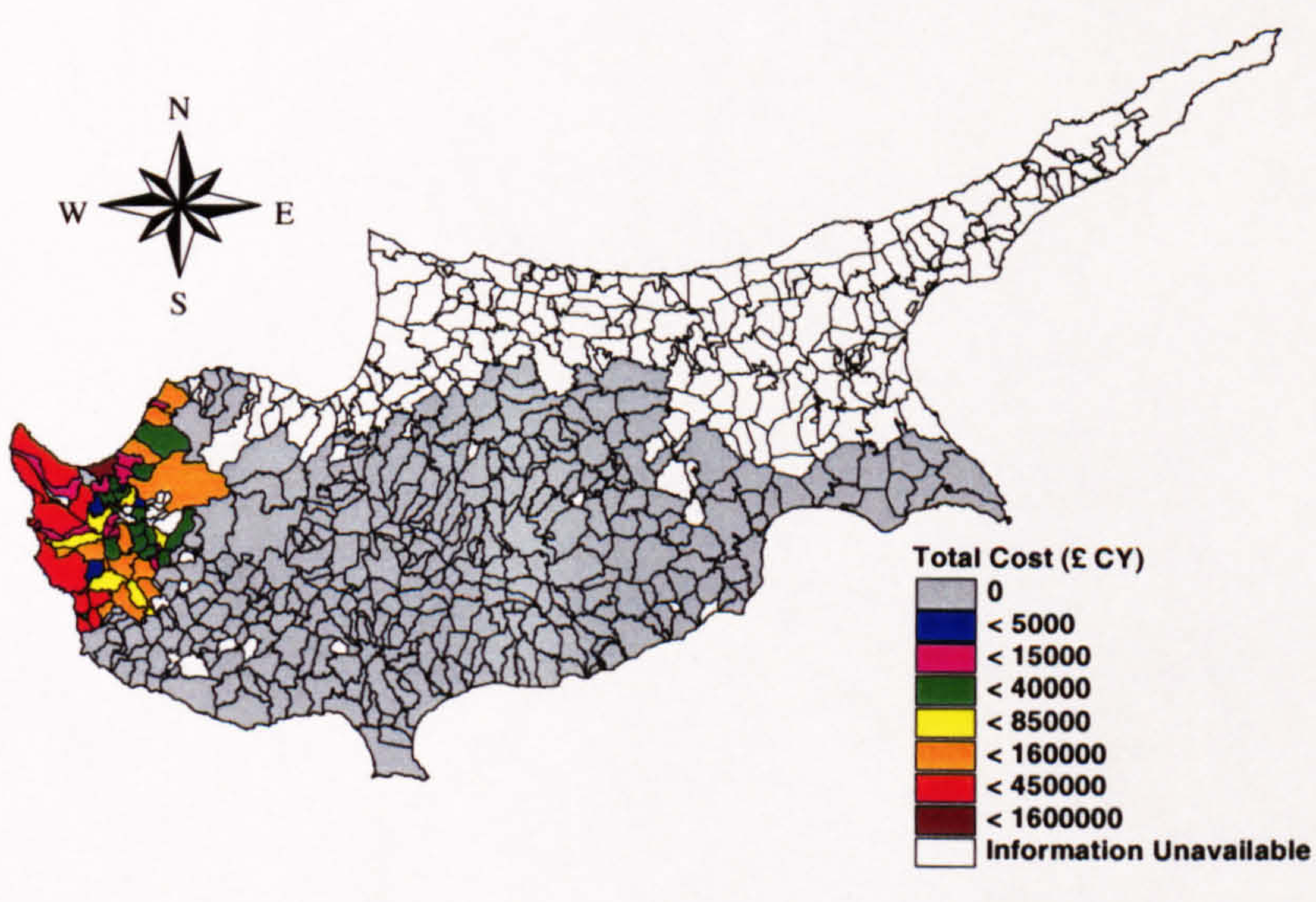


Figure 4.8. Estimation of the earthquake risk (i.e. total damage cost) based on the total dwelling stock, the predicted intensities and the mean damage ratios; caused by the earthquake which occurred on the 23rd of February 1995 with $M_S = 5.7$

4.2.2.3 PART III – FATALITIES AND INJURIES

The last routine (see Figure 4.9) deals with the estimation of the fatalities and injuries (typical maps shown in Figure 4.10). This is achieved by the use of the Mean Fatalities Ratios (MFR) and the Mean Injuries Ratios (MIR), the population presence that is dependent on the time of occurrence (i.e. month of year and hour of day) of the events as well as the population distribution. The databases required for Part III are presented in Table 4.4.

Part III follows the same procedure as Part II (i.e. for intensities greater than V possible life losses are assumed and for intensities lower than V the process terminates).

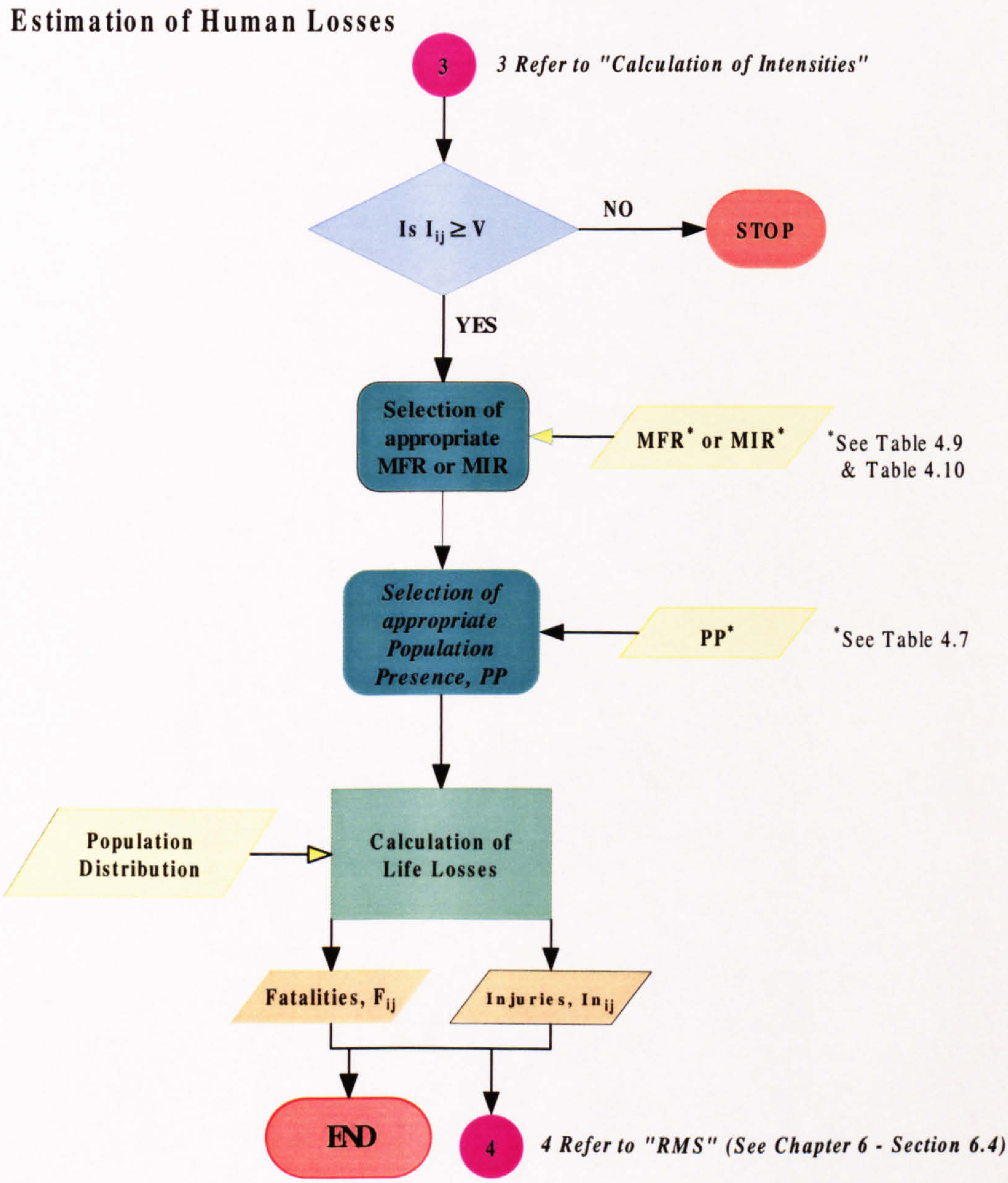


Figure 4.9. Routine for computer simulation Part III "Estimation of Human Losses"

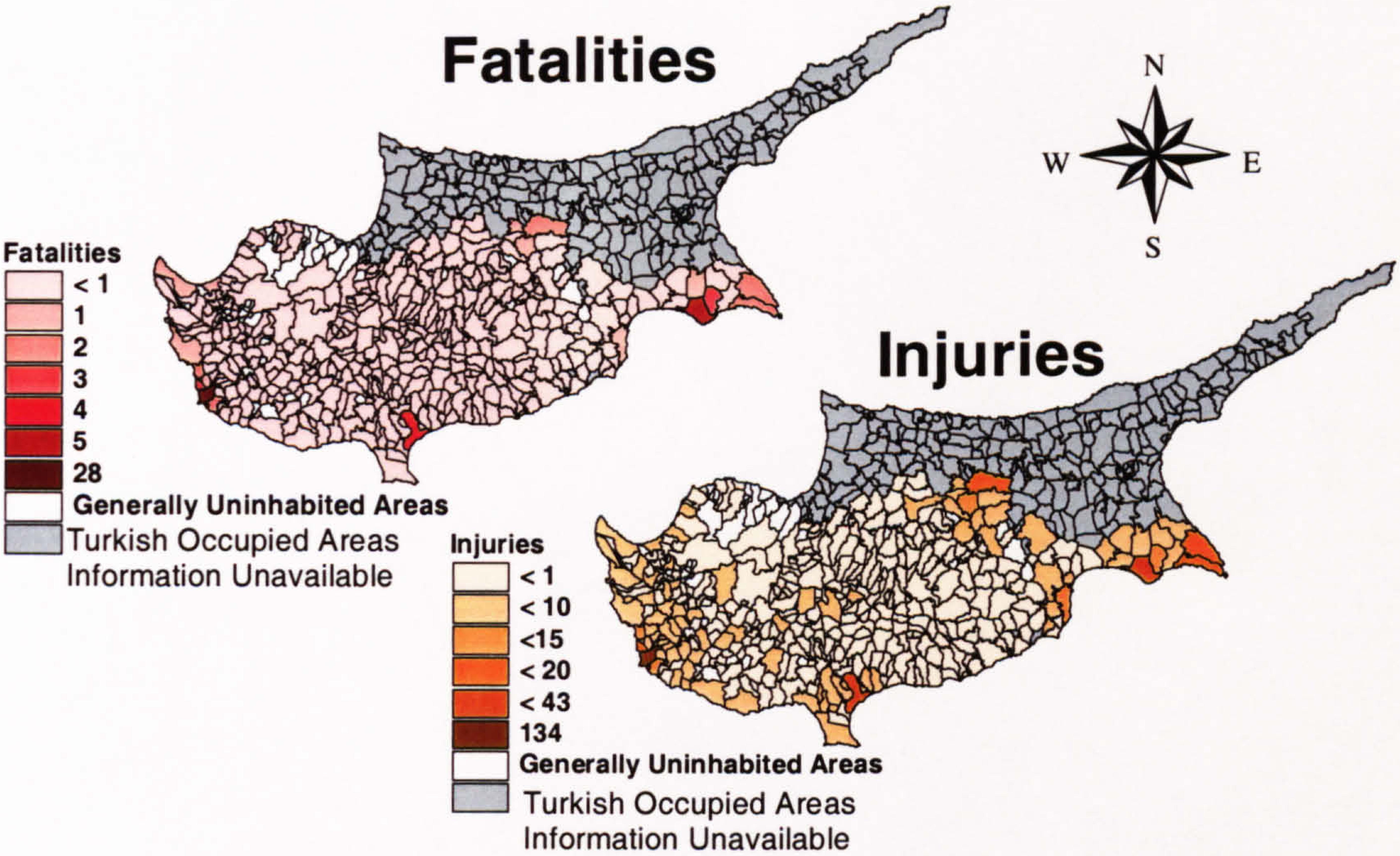


Figure 4.10. Expected injuries and fatalities if last century's earthquakes were to be repeated at the same epicentres and magnitudes with the current population and building stock

Table 4.4. Input databases for PART III – Fatalities and Injuries

NAME		CHARACTERISTICS
MFR	MFR_{ijk}	Mean Fatalities Ratios for each intensity and each type of building
MIR	MIR_{ijk}	Mean Injuries Ratios for each intensity and each type of building
Population Distribution	PD_{ik}	Number of population in each area and each type of building
Population Presence	PP_{ik}	Percentage of the population either indoors or outdoors

*Different types of buildings are denoted by the variable k

4.3 MODEL MODIFICATIONS/IMPROVEMENTS

Many problems were encountered once the initial model was put into operation. These were identified from the comparisons of the predicted damages to the known true damages for specific well documented earthquakes. In the following section these problems will be presented together with the actions taken for their resolution.

4.3.1 LIMITS OF THE ATTENUATION EQUATIONS ADOPTED

A problem developed due to the way the attenuation equations adopted, are defined, which limits the use of the equations for intermediate earthquakes to Rcer of 40km. The initial model was considering that the acceleration and therefore the intensities for areas with a hypocentral distance of Rcer < 40km to be zero. That was obviously wrong and to correct it, it was assumed that for the areas within such distances the maximum intensity calculated at Rcer = 40km would be adopted. The process followed to correct this error is shown in Figure 4.11.

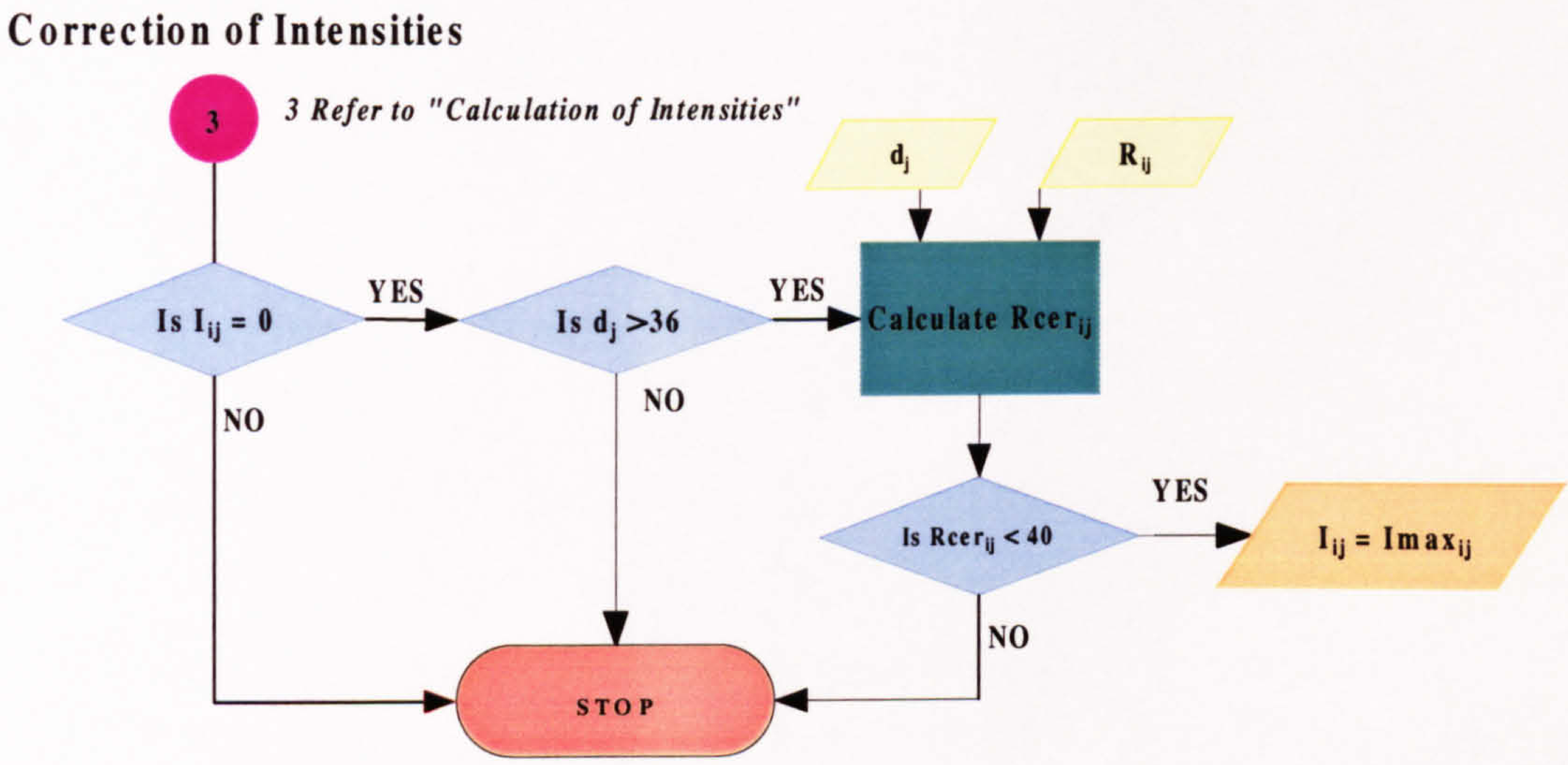


Figure 4.11. Routine for computer simulation Part Ic "Seismic Hazard Assessment – Correction of Intensities"

4.3.2 EARTHQUAKE CATALOGUE

4.3.2.1 LIMITING THE CATALOGUE

Based on the Modified Mercalli Intensity (MMI) scale, structural damage starts at intensity VI. In an attempt to identify the magnitude value which would cause such intensity to be experienced at the epicentre, the attenuation equations derived by Theodulidis and Papazachos (1992) were used. For the calculation of the earthquake hazard it was decided to use only the events of the earthquake record with $M_S \geq 4.5$ (a total of 110 events). The values obtained for both alluvial sites (i.e. S=0) and rock sites (i.e. S=1) are listed in Table 4.5, the calculations are included in Section 1 of Appendix C.

Table 4.5. Limiting magnitudes for the earthquake catalogue

	I_{MM}	Alluvial Sites (S=0)	Rock Sites (S=1)
Shallow depth	VI	4.4	4.0
Intermediate depth	VI	4.5	3.8

The selection of $M_S = 4.5$ as the limiting factor for the earthquake record was also based on the M_{MIN} limitation of the attenuation equations adopted in this research which is $M_S = 4.5$ (Table 3.2).

Another factor that necessitated the limitation of the number of events involved in the analysis of the hazard, was the problems encountered during trials involving the whole record. During these trials the software (MS Excel) proved unable to cope with such large amount of data and the modelling process was constantly interrupted.

4.3.3 MEAN DAMAGE RATIOS – MDR

The model was also changed so as to select more refined MDRs. This was necessary to avoid attributing damage due to intensities that are not supposed to cause damage e.g. 5.5-5.9 for superior construction. Whilst initially the model was working based on a range of values (e.g. for $5.5 \leq I \leq 6.4$ it was using the MDR for VI) now a linear interpolation for the MDR values was created (see Table C-1 in Section 2 – Appendix C).

4.3.4 POPULATION PRESENCE

The identification of the importance of the exact location of the population during an earthquake and the incorporation of a "time of occurrence" option into the framework, initially introduced the selection of either a day or night pattern. The model estimated the fatalities and injuries of all the earthquakes twice. Firstly it assumed that all earthquakes occurred during the day (8am-7pm) and secondly that they all occurred during the night (7pm-8am).

The high winter/summer fluctuation of the island's population though necessitated the introduction of a seasonal option as well. The months assigned to each category are given in Table 4.6. The model was therefore set up to provide four different time zones, Summer Day, Summer Night, Winter Day and Winter Night. The exact month and time, the earthquake occurred, is now involved. The four different time zones were numbered from 1 to 4 and by checking the month and hour each earthquake occurred the appropriate value was assigned to each event. The model checks first the time zone value of the earthquake, then selects the appropriate percentage of population presence and finally calculates either the fatalities or injuries, using the appropriate mean fatality ratios (MFR) or mean injury ratios (MIR). The seasonal, day and night population presence patterns used in the model are listed in Table 4.7. Figure 4.12, presents the seasonal population distribution in the various types of buildings.

Table 4.6. Months associated with each category

Summer	Winter
April	October
May	November
June	December
July	January
August	February
September	March

Table 4.7. Seasonal, Day and Night Population Presence Patterns

Time Zone	No	Living Quarters	Public Establishments	Private Establishments	Other Establishments (i.e. Hotels) ☆	Outdoors
Summer Day	1	20%	20%	20%	80% x 30%	40%
Summer Night	2	70%	0%	20%	80% x 60%	10%
Winter Day	3	25%	25%	25%	40% x 50%	25%
Winter Night	4	80%	0%	15%	40% x 90%	5%

☆ The population of the other establishments (i.e. hotels) is considered to be extra to the total population of the island. This extra population was estimated from the assumption that every bed is a person. An assumption was made that during the high season (i.e. summer) the total occupancy is 80% of the beds. During a low season (i.e. winter) the total occupancy drops to 40% of the beds

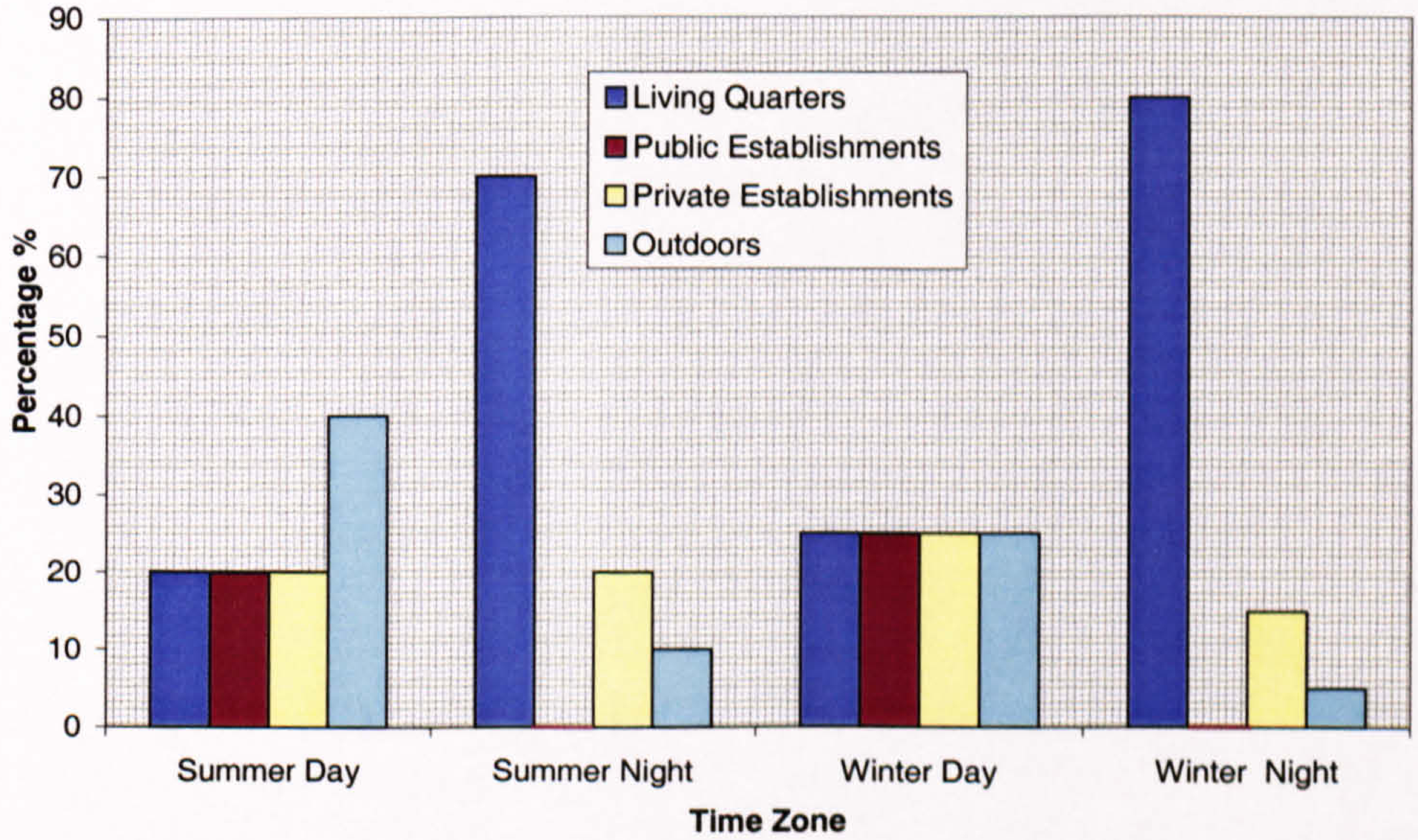


Figure 4.12. Seasonal Day/Night Population Distribution

The introduction of the seasonal option required the more specific division of the day and night hours Table 4.8. The climate of Cyprus allows significantly longer days during the summer than during the winter. For the purposes of this research the separation of the day and night hours is not by any means associated with the actual daylight hours the only parameter involved in this selection was the average hours Cypriots spend outdoors during summer and winter months.

Table 4.8. Summer and Winter - Day and Night Hours

Summer		Winter	
Day	Night	Day	Night
16hrs	8hrs	12hrs	12hrs
7am-11pm	11pm-7am	8am-8pm	8pm-8am

4.3.5 Mean Fatality Ratios (MFR) & Mean Injury Ratios (MIR)

As it was mentioned in chapter 3, since the number of collapsed buildings influences the fatality and injury totals, it was decided to obtain the necessary percentages suitable for their prediction through the modification of the MDRs used for the prediction of the damaged buildings.

A small study which involved raising these MDRs to various powers, and the comparison of the estimated fatalities and injuries to the known human losses due to specific earthquakes (i.e. 1953, 1995, 1996) enabled the selection of the most appropriate modification factors, 3.7 for fatalities and 2.8 for injuries.

Two new sets of MFRs and MIRs, were calculated (see Table 4.9 and Table 4.10). The MFRs and MIRs were then multiplied with the population distribution to get the fatalities and injuries (shown in Figure 4.10).

Table 4.9. Mean Fatality Ratios (MFRs)

MDR	superior			standard substandard
MMI	< 4 storeys	>4 storeys	Halls	All
V	0%	0%	0%	0%
VI	0%	0%	0%	0.003%
VII	0.002%	0.0002%	0.001%	0.04%
VIII	0.03%	0.005%	0.04%	0.51%
IX	0.59%	0.11%	1.16%	6.62%
X	3.37%	1.02%	15.12%	43.8%

Table 4.10. Mean Injury Ratios (MIRs)

MDR	superior			standard substandard
MMI	< 4 storeys	>4 storeys	Halls	All
V	0%	0%	0%	0%
VI	0%	0%	0.0003%	0.04%
VII	0.02%	0.005%	0.012%	0.26%
VIII	0.21%	0.06%	0.26%	1.84%
IX	2.06%	0.59%	3.44%	12.81%
X	7.68%	3.12%	23.92%	53.54%

4.4 VALIDATION OF MODEL

The intensities, damaged buildings, and economic losses as well as human losses were selected as the parameters to be examined as part of the verification process of the model. These parameters were considered for the few earthquakes for which information exists.

4.4.1 INTENSITIES

The obtained isoseismal / damage data of three earthquakes (1953, 1995, 1996) were plotted and compared to the predicted intensities estimated using the equation derived by Theodulidis and Papazachos (1992). The results were better than expected with the real and predicted intensities being very similar (see Figure 4.13, Figure 4.14, Figure 4.15). This validates the selection of the attenuation equations as well as the data relating to the earthquake magnitude and location.

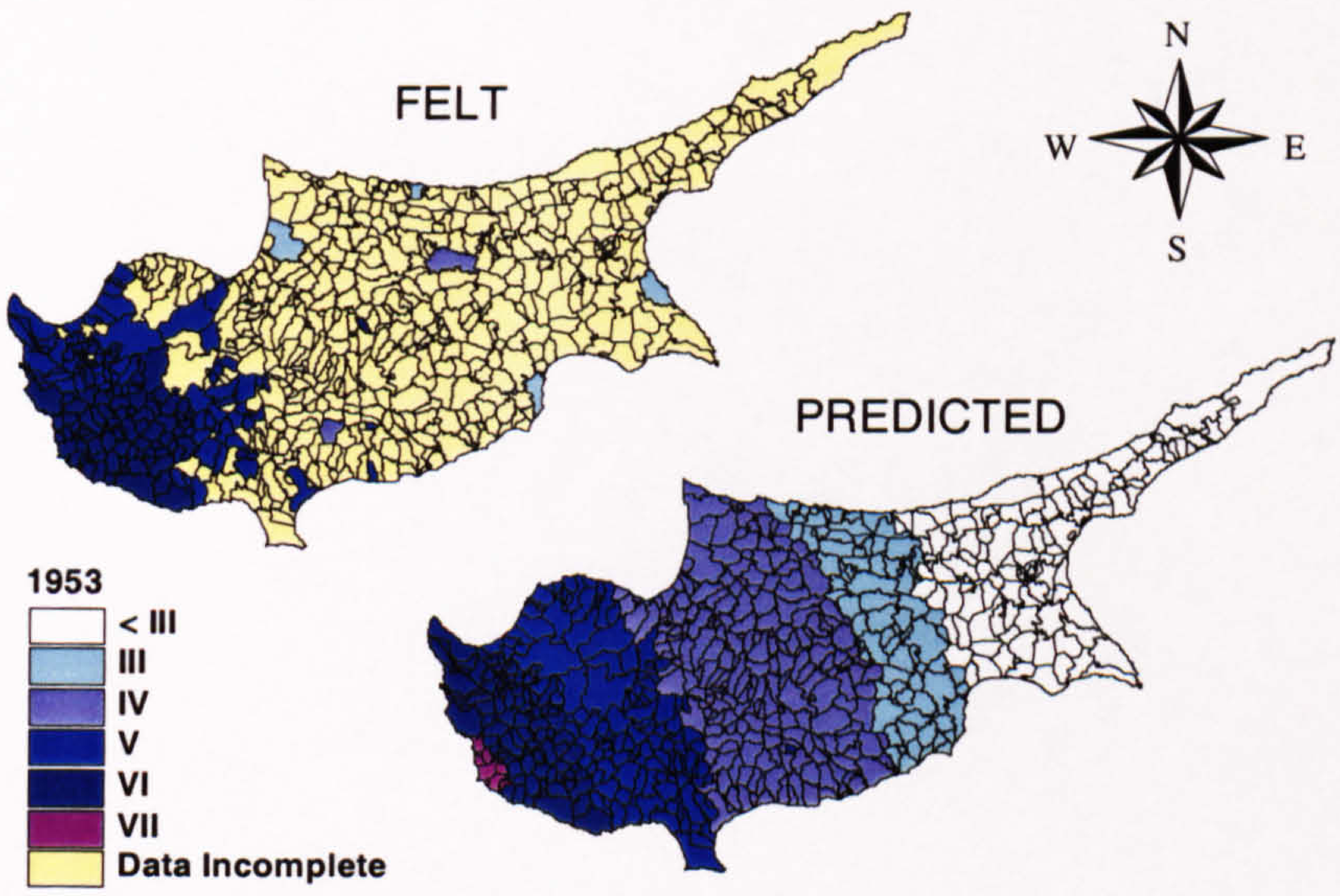


Figure 4.13. Felt and predicted Intensities in various areas of the island as a result of the 10th of September 1953 double earthquake (M_S=6.1 M_S=6.0)

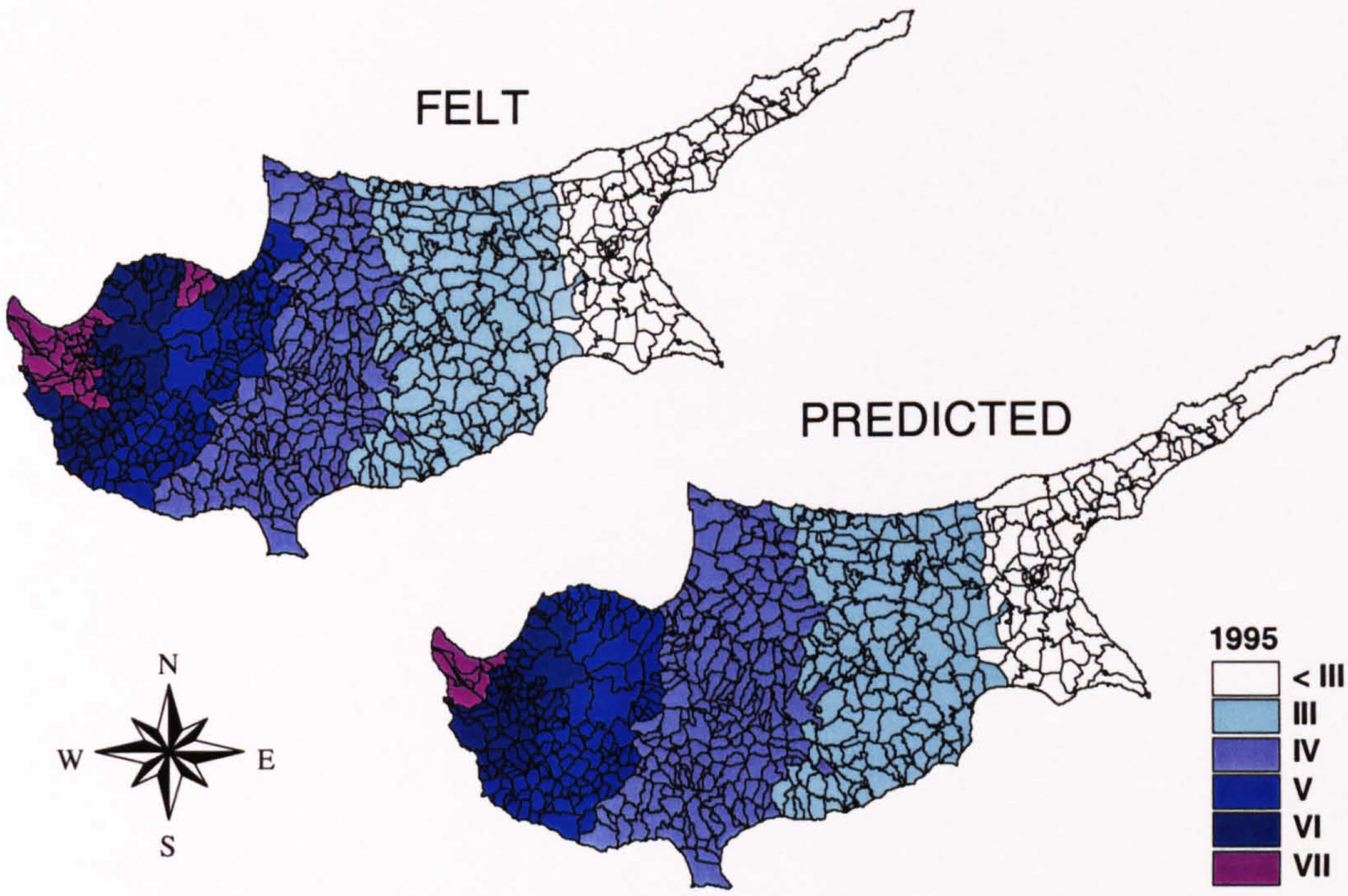


Figure 4.14. Felt and predicted Intensities in various areas of the island as a result of the 23rd of February 1995 earthquake (M_S=5.7)

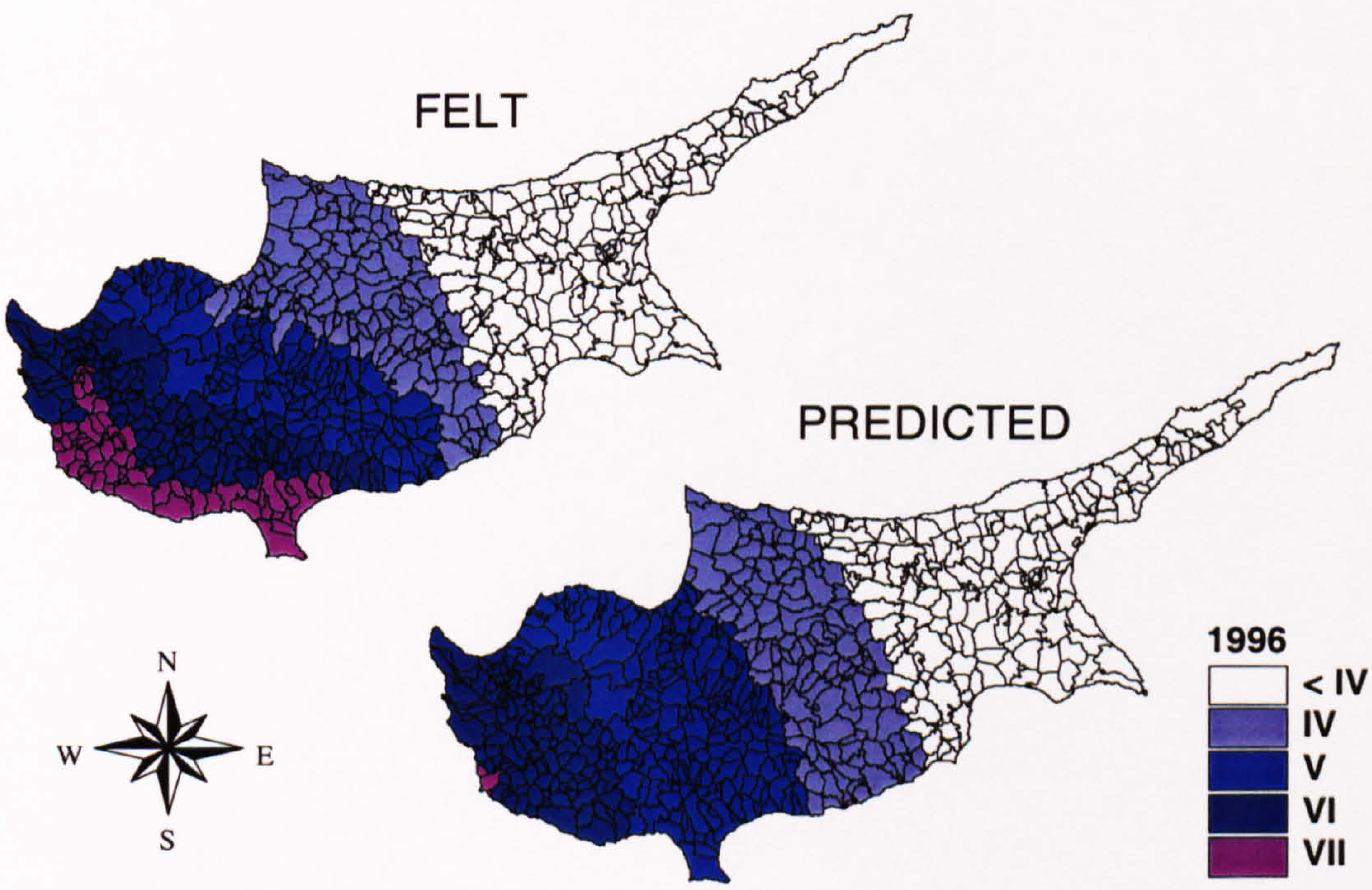


Figure 4.15. Felt and predicted Intensities in various areas of the island as a result of the 9th of October 1996 earthquake (M_S=6.5)

It should be pointed out that the predicted intensities, though they account for the geology, do not take into consideration the vulnerability of the building stock.

4.4.2 Calibration of MDR and Validation of Cost

The damage costs incurred due to the earthquakes of 1995 and 1996 were obtained from the Rehabilitation and Reconstruction Services, Town Planning Department of the Ministry of Interior (Kyriakides, 2000). The 1995 earthquake was chosen for the validation process since it is believed that the data concerning that event are more complete, whereas the 1996 data appear less reliable or incomplete. The magnitude of the events, the number of fatalities and injuries as well as the number of compensation applications and the total costs of the restorations have been gathered and are presented in Table 4.11.

These data were used in an attempt to check whether the predicted damage costs are realistic. Various factors may affect the comparison of the two values. The total restoration costs are the money paid by the government for compensation. It does not necessarily mean that this is the actual total damage cost of the earthquake since many people would not have made a claim for their damaged property, or they might have had private insurance which paid for the damage, or unoccupied buildings have not been repaired.

Table 4.11. Fatalities, Injuries, Damage Applications and Costs of restoration caused by the earthquakes of 1995 and 1996 in Cyprus (Kyriakides, 2000)

EARTHQUAKE EFFECT		23 February 1995	9 October 1996
Magnitude		M_S= 5.7	M_S = 6.5
Fatalities		2	1
Injuries		21	13
Damage Applications	Nicosia	400	500*
	Limassol	-	8000
	Paphos	3500	3000
	Larnaca	-	500*
Total		3900	12000
Cost of Restoration		£3,800,000 CY	£4,015,764 CY

*The number of damage applications given for the Nicosia and Larnaca for the 1996 event were selected discretely since for these towns the data obtained gave a single number of 1000 for both.

The calibration process initially examined three cases with an excessive prediction of 1377 totally damaged buildings to a rather moderate prediction of 50 totally damaged buildings. All three cases are presented together with their corresponding assumptions in Section 3 of Appendix C. Due to the fact that the last case reduced the number of the predicted damaged buildings to a much lower value than the real value, a fourth case which involved the adjustment of the mean damage ratios (Table 4.12) was also examined (results shown earlier in Figure 4.7).

Table 4.12. Mean Damage Ratios adopted for this research

MDR	superior			standard substandard
MMI	< 4 storeys	>4 storeys	Halls	All
V	0%	0%	0%	0%
VI	0%	0%	1%	6%
VII	5%	3%	4%	12%
VIII	11%	7%	12%	24%
IX	25%	16%	30%	48%
X	40%	29%	60%	80%

In addition to the number of damaged buildings, and in an attempt to be more accurate, the total cost of the damage was also examined. The average of the cost of the adobe and stone buildings given by KORONIDA (see Table B-5 - Appendix B) was calculated and then using the inflation rates (see Table B-7 - Appendix B) adjusted to current prices. It must be noted that only 50% of each inflation rate was used, since the total value is considered to find the price of a new building (built today) whereas in this case the current value of an existing building (which is not necessarily well maintained) is required. As far as the Reinforced Concrete buildings (houses or apartments) are concerned, their values were taken from Table B-6 in Appendix B. For each district the appropriate price was used. Since the price given for RC Houses includes the price of the land, a final adjustment involved the subtraction of the estimated land value of £20000 CY pounds from the average total amount. The final costs used for this study are given in Table 4.13 and are constant 1996 prices.

The predicted total damage cost for the given earthquake was found to be equal to £5,930,404 CY as compared to the actual costs of restoration £4,015,764 CY (1996 prices). As it was mentioned before, the restoration costs given by the Rehabilitation and Reconstruction Services are likely to be a lower bound to the actual costs. Therefore, the results obtained are considered satisfactory.

Table 4.13 Costs for the three types of construction in 1996 prices for the Living Quarters and Private/Public Establishments

TYPE	Districts	Type of Construction		
		Adobe / Stone	Reinforced Concrete	
			Houses	Apartments
Living Quarters	NICOSIA	£6185	£51980	£38787
	FAMAGUSTA	£6185	£38860	£23458
	LARNACA	£6185	£42364	£31694
	LIMASSOL	£6185	£44960	£33970
	PAPHOS	£6185	£44300	£34320
Establishments	NICOSIA	£51980	£51980	£51980
	FAMAGUSTA	£38860	£38860	£38860
	LARNACA	£42364	£42364	£42364
	LIMASSOL	£44960	£44960	£44960
	PAPHOS	£44300	£44300	£44300

The verification studies showed that despite the use of such crude mean damage ratios, relatively accurate damages were predicted. When more appropriate information becomes available it can be included in the model and better predictions should be expected.

The value of the elements at risk is another parameter involved in the calculation of earthquake risk. Various assumptions (i.e. mainly assuming a constant value for the same type of buildings within a district) were involved in dealing with the cost, which unquestionably might reduce the accuracy of the results of the model. Despite the fact that the limitations of these assumptions are appreciated, they were necessary due to the limited available information. If and when a better database is available it can be employed for a more realistic result. Nevertheless, the verification of the results proved that the model predictions are very promising. A sensitivity study will examine the effect of the MDR values in the next chapter.

4.4.3 FATALITIES AND INJURIES

In order to verify the predictive models for fatalities and injuries, comparisons are made with the actual losses experienced in the past. Last century's earthquake catalogue was used to predict the fatalities and injuries likely to be caused, if they were to occur assuming todays building and population distribution. The results showing the distribution of loss were presented in Figure 4.10.

A comparison of the actual and predicted, earthquake fatalities and injuries for the four main earthquakes is presented in Table 4.14. The results are very good since the predicted fatalities and injuries are close to the actual ones. It should be noted that the predictions are made with the current building and population distribution and, hence, a very direct comparison with the actual data is not appropriate.

Table 4.14. Fatalities and Injuries in Cyprus due to the main earthquakes of the last century and comparisons with predictions

Date	Or. Time			Ms	Fatalities		Injuries	
	Hrs	Min	Sec		Actual	Predicted	Actual	Predicted
20th January 1941	03	37	00	5.9	-	4	24	56
10th September 1953	06	05	00	6.0	40	31	150	140
23rd February 1995	21	03	04	5.7	2	4	21	27
9th October 1996	13	10	52	6.5	2	6	85*	36
			Total		44	45	282	252

*Believed not to be accurate and rather overestimated

Whilst it is appreciated that the procedure followed (i.e. the use of the mean fatality and injury ratios based on the relation between collapses and fatalities and injuries) is a crude way of approaching this problem, it is necessitated due to the lack of more suitable models. However, the results obtained are promising and no further refinement of the model is necessary for the purposes of this work.

4.5 DISCUSSION

The use of a digitised map for the better visualisation of the results proved to be a useful tool. Furthermore, the use of detailed databases with a common reference point facilitated the smooth operation of the model.

However, for the input data to be better represented, it is appropriate at a future stage to transfer the techniques to a commercial GIS software. This would enable existing maps of population statistics and hydrogeology, for example to be readily incorporated into the framework. The potential exists for relevant geophysical parameters (including soil thickness, rock stiffness and topography) to be modelled as uncertain input variables within the GIS simulation framework. Besides the simulation of future event scenarios, GIS clearly offers additional benefits in ERA. One example is the easier calculation of emergency response times in the event of a natural disaster.

In general the performance of the model is very satisfactory. This will be demonstrated better in chapter 6 where the general discussion and risk management strategies are presented.

PARAMETRIC STUDIES

5.1 PARAMETRIC STUDIES

5.1.1 INTRODUCTION

In an attempt to establish the effect of the variability of the parameters involved in the estimation of earthquake risk on earthquake damage, cost, fatalities and injuries, a parametric study is performed.

The parameters examined are divided into two groups. The first group includes the parameters regarded as characteristics of earthquakes i.e. epicentre location, depth and magnitude. The second group involves the geology of the area under consideration, the attenuation relationships selected, the vulnerability of the buildings and the population presence.

5.1.2 EPICENTRE LOCATION, DEPTH AND MAGNITUDE

5.1.2.1 INTRODUCTION

Besides its magnitude the two other geometric characteristics of an earthquake are its epicentre and depth.

The procedure for magnitude estimation and the uncertainties involved were explained and presented in chapter 2. Various factors were shown to affect the determination of the epicentre and depth of an event. According to Theodulidis (2000), they are dependent on the magnitude of the event, the configuration of the seismological network monitoring the broader area, as well as on the experience of the analyst (seismologist) who is responsible for determining earthquake location.

From a statistical point of view, Theodulidis (2000) suggested that for $M \geq 4.5$ for the Aegean and the surrounding area for the period (1970-2000) the majority of the events have errors in their epicentres and depths less than 10km. However, it is appreciated that, in the near-field of large destructive events ($M \geq 6.5$) epicentre has almost no meaning since it is just a point on a rupture surface of approximately 30km length and 13km width. Theodulidis (2000) stated that in such cases one should carefully define the rupture fault surface and if possible the centre of energy release, with the latter possibly being completely different from the epicentre on the main shock. Time limitations and lack of data did not allow the involvement of this special characteristic of the destructive earthquakes into the model. However, future work should look into this aspect further.

Papazachos and Papaioannou (1999) suggested that in general the accuracy for the epicentres is of the order of 15km (with a rather uniform probability of occurrence in the whole area) and for the focal depths of the order of 20km. Furthermore, Papaioannou (2000) advised that as far as the estimation of the earthquake magnitude is concerned and based on data from the ISC since 1964 the accuracy for the magnitude (m_b) is of the order of 0.2.

Therefore, as part of the research in the identification of the seismic hazard and the estimation of the earthquake risk, it was decided that the location of the epicentres as well as the depth had to be examined.

5.1.2.2 Epicentre Location

The earthquake epicentres were translated and modified earthquake catalogues were created, which were used to make new predictions of the total damage cost from 1894 to 1997. Sixteen cases were examined. As it was mentioned above the accuracy for the epicentres is of the order of 15km and subsequently each epicentre was shifted, from its recorded original position to 16 different positions, around two circles of 10km and 20km radius (Figure 5.1).

The values that needed to be added to the Longitude (N°) and Latitude (E°) of each epicentre were calculated using basic geometry.

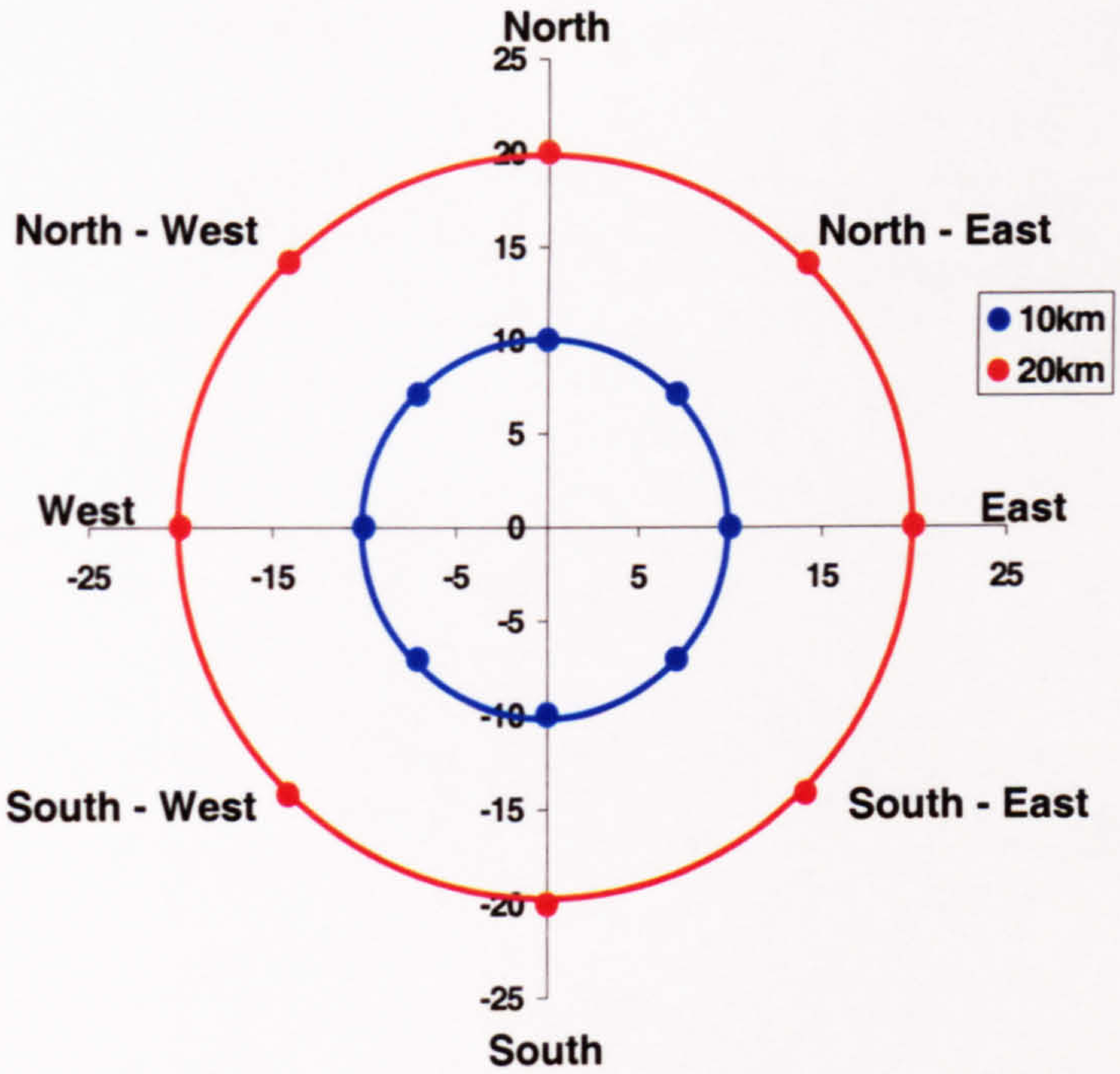


Figure 5.1. The sixteen positions for the parametric studies involving the location of the earthquake epicentre in both 10km and 20km radius

Table 5.1 presents the results for the different total damages, total damage costs, total fatalities and total injuries.

Table 5.1. Results of the Parametric Studies for the earthquake epicentres

	Positions	Damages (No of total damaged buildings)	Total Damage Cost (£ Cyprus Pounds)	Fatalities	Injuries
	Original	24327	£767,814,799	41	342
10km	East	25433	£812,002,755	70	454
	West	20356	£620,514,401	31	273
	North	24349	£750,915,079	38	326
	South	22451	£740,843,134	33	306
	North East	26588	£839,623,161	77	494
	North West	21487	£647,673,112	32	281
	South East	25223	£841,637,865	41	354
	South West	19719	£616,431,711	25	256
	Average	23201	£733,705,152	43	343
	σ	2552	£95,103,297	19	87
20km	East	21893	£649,321,347	39	311
	West	19794	£611,356,503	35	288
	North	25701	£801,794,204	48	353
	South	16625	£536,476,249	22	221
	North East	28058	£893,440,044	64	439
	North West	21487	£647,673,112	32	281
	South East	19009	£604,133,049	38	297
	South West	16082	£505,409,536	23	226
	Average	21081	£656,200,505	38	302
	σ	4169	£130,599,705	14	70

The spatial distribution of the total damage is presented in Figure 5.2. As it can be seen by moving the epicentres to the north east, the total damage increases significantly. This is mainly due to the fact that the epicentres in the South were moved closer to the island and, in some cases, though initially the events had epicentres in the sea they are now assumed to be located inland. The damage costs, fatalities and injuries showed an almost identical pattern (Section 1 - Appendix D).

The results obtained from this study indicate that the epicentre location is an important parameter and its position affects earthquake risk significantly. Taking as an example the total damages it can be seen that whilst the minimum values are around 0.7 of the average (original values) the maximum estimated damages reach 1.12.

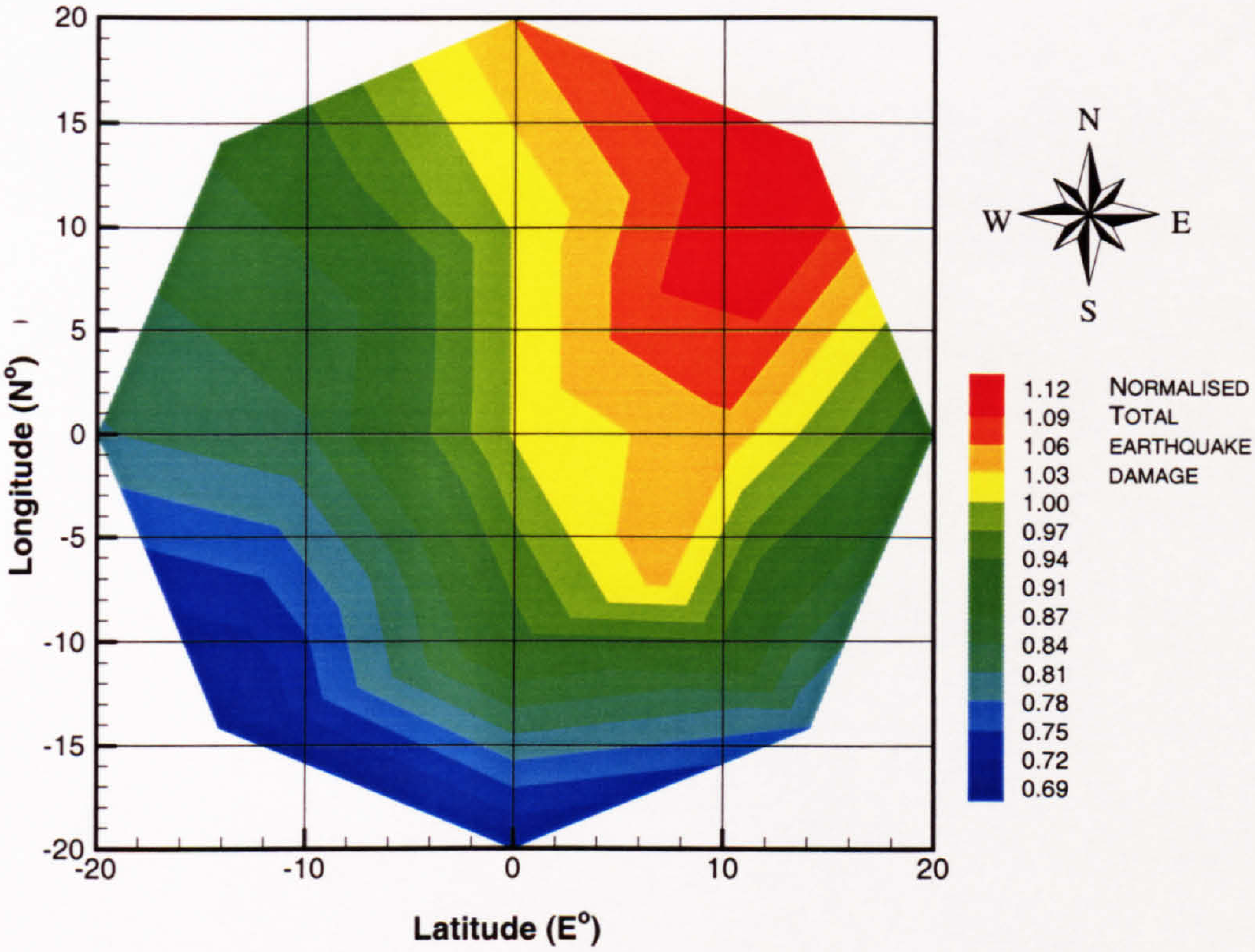


Figure 5.2. Spatial distribution of the variations in the normalised total earthquake damages

5.1.2.3 DEPTH

As it was mentioned earlier on, Papazachos and Papaioannou (1999) suggested that for the focal depth the accuracy is of the order of 20km. Hence, a similar approach to that suggested for the parametric study of the epicentres was applied to the depths, with the earthquakes recorded depth increased (+) and decreased (-) (naturally not above ground level) by 20km (Table 5.2). Table 5.2 presents the results of this study.

Table 5.2. Results of the parametric studies for the earthquake depth

	Study	Damages (No of total damaged buildings)	Total Damage Cost (£ Cyprus Pounds)	Fatalities	Injuries
1	Original	24327	£767,814,799	41	342
2	Depth + 20km*	55773	£1,724,285,379	66	596
3	Depth - 20km*	21390	£693,700,629	47	364
4	Average	38581.37	£1,208,993,003	56	480

**Depth + 20km* - means 20km deeper
Depth - 20km means 20km shallower (i.e. nearer to the surface)

In this study the results are surprising since the damage cost increases by 150% when the earthquakes are deeper but only decrease by 10% when the hypocentres are nearer to the surface. This is attributed to specific offshore earthquakes whose impact increases in distant locations when the depth increases. However, the injuries and fatalities increase when the earthquakes are shallower. The total damages (shown in Figure 5.3) and total damage costs (see Figure D-4 - Appendix D) had their original values lying within the values estimated when the depths were decreased and increased by 20km. The original values for the fatalities (Figure 5.4) and injuries (see Figure D-5 - Appendix D) were the minimum obtained. Again this emphasises the importance of the depth variability in the determination of risk.

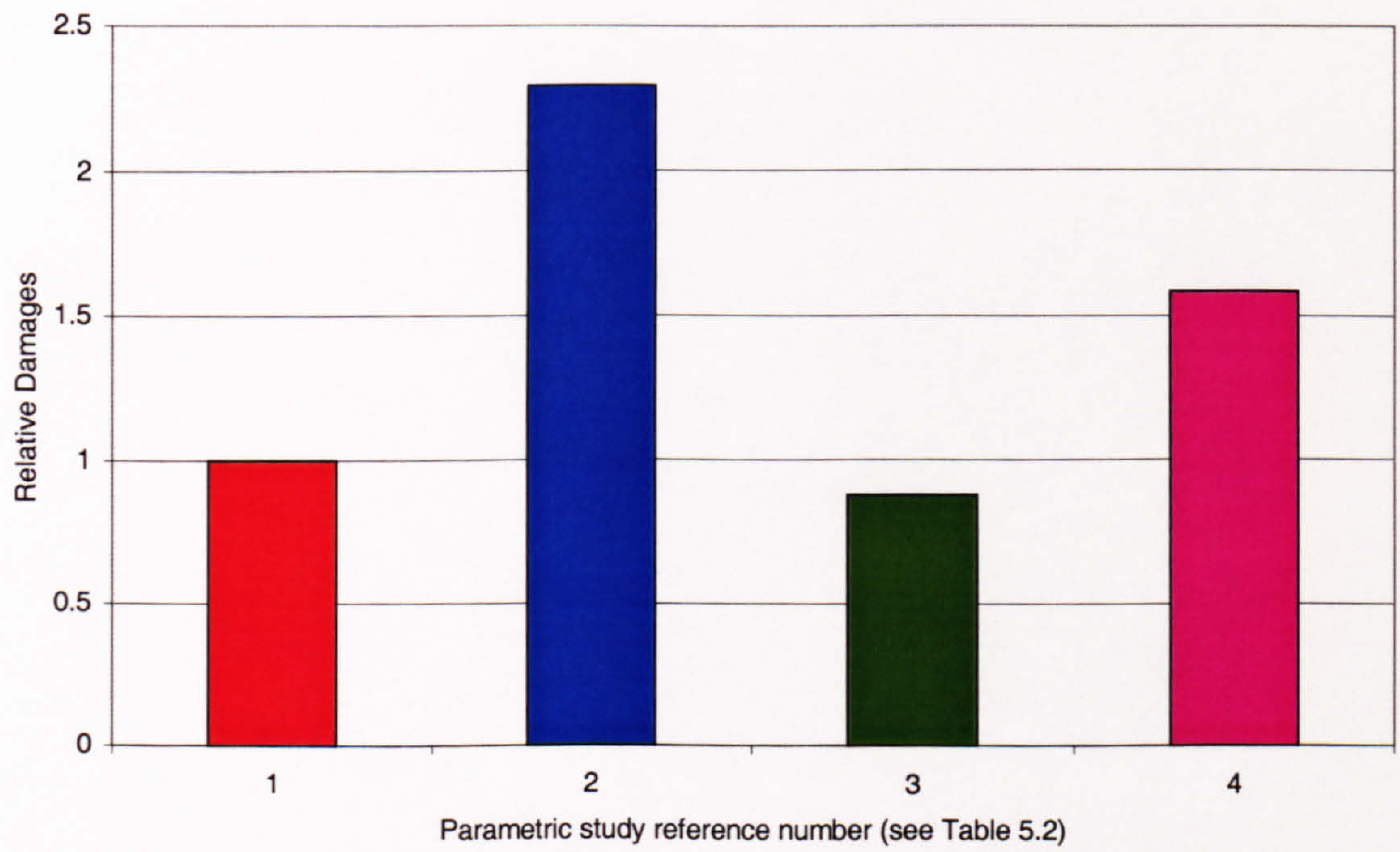


Figure 5.3. Comparison of the normalised total damage results obtained from the parametric studies for the earthquake depth

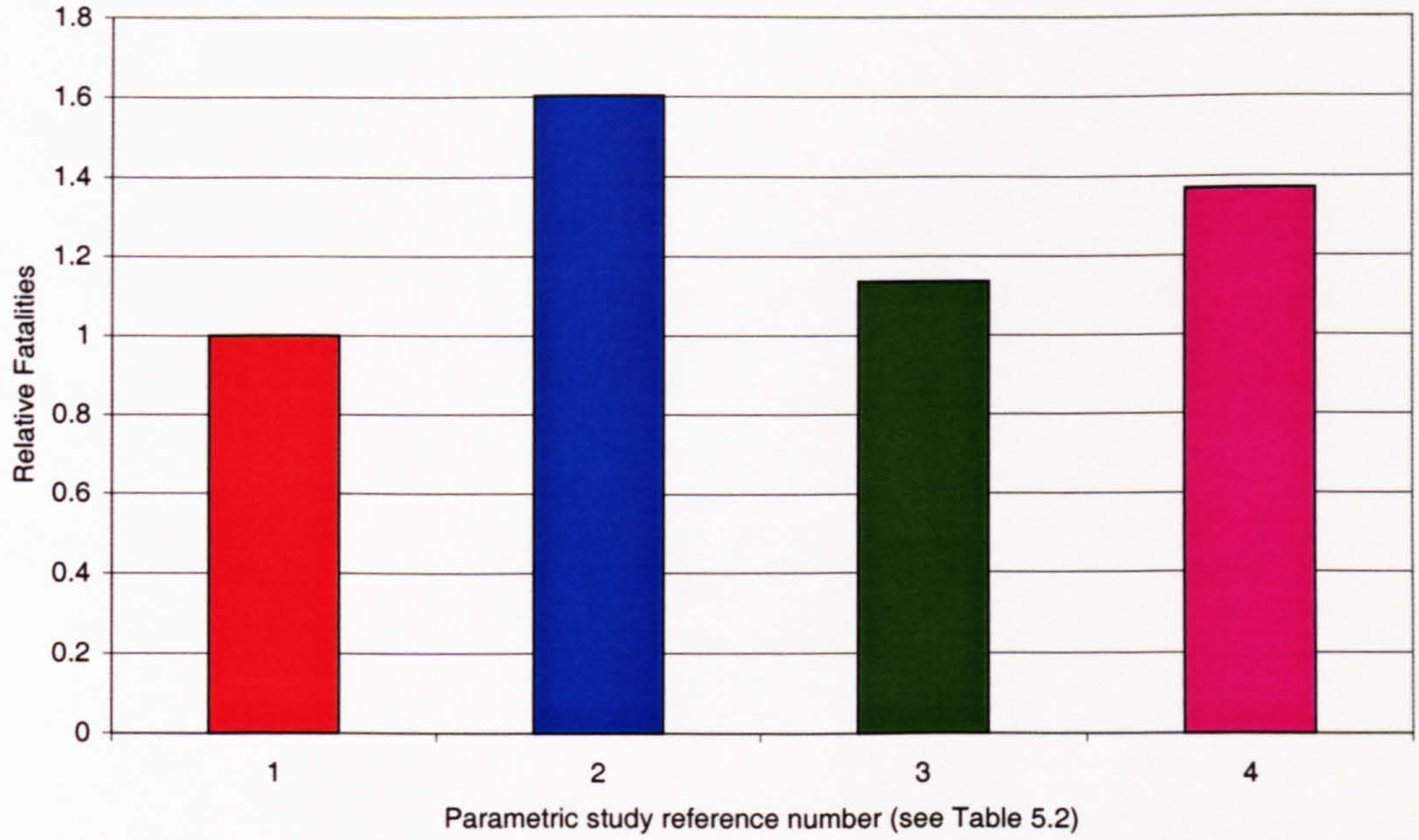


Figure 5.4. Comparison of the normalised total fatalities results obtained from the parametric studies for the earthquake depth

5.1.2.4 MAGNITUDE

The magnitude estimation of an earthquake is a parameter that causes many disagreements within the seismological research society. The various magnitude scales as well as the fact that different stations receive higher or lower amplified seismic waves, due to the geological sequences present between the station and the epicentre, are mainly the reasons for these inconsistencies.

Many scaling relations are present and could be applied to obtain homogeneous data. For the purposes of this research the appropriate scaling relations were applied and it is believed that the data included in the resulting catalogue are homogeneous as explained in section 3.2.3.

As mentioned in section 5.1.2.1 according to Papaioannou (2001) the accuracy for the m_b in the ISC records since 1964 is of the order of 0.2. It was decided therefore to use a similar increment/decrement to the magnitudes (M_S) of the earthquake events included in the catalogue used. The results of the parametric studies for the earthquake magnitude are presented in Table 5.3. The plots for the total damage costs, total fatalities and total injuries can be found in Section 3 of Appendix D.

Table 5.3. Results of the parametric studies for the earthquake magnitude

	Study	Damages (No of total damaged buildings)	Total Damage Cost (£ Cyprus Pounds)	Fatalities	Injuries
1	Original	24327	£767,814,799	41	342
2	M_S +0.2	38407	£1,226,343,629	98	639
3	M_S –0.2	14865	£463,341,771	21	197
4	Average	26635	£844,842,700	60	418

Figure 5.5 presents the normalised difference of the total damages between the three variations of this study. As it can be seen the error in the magnitude determination can change the results by up to 50%.

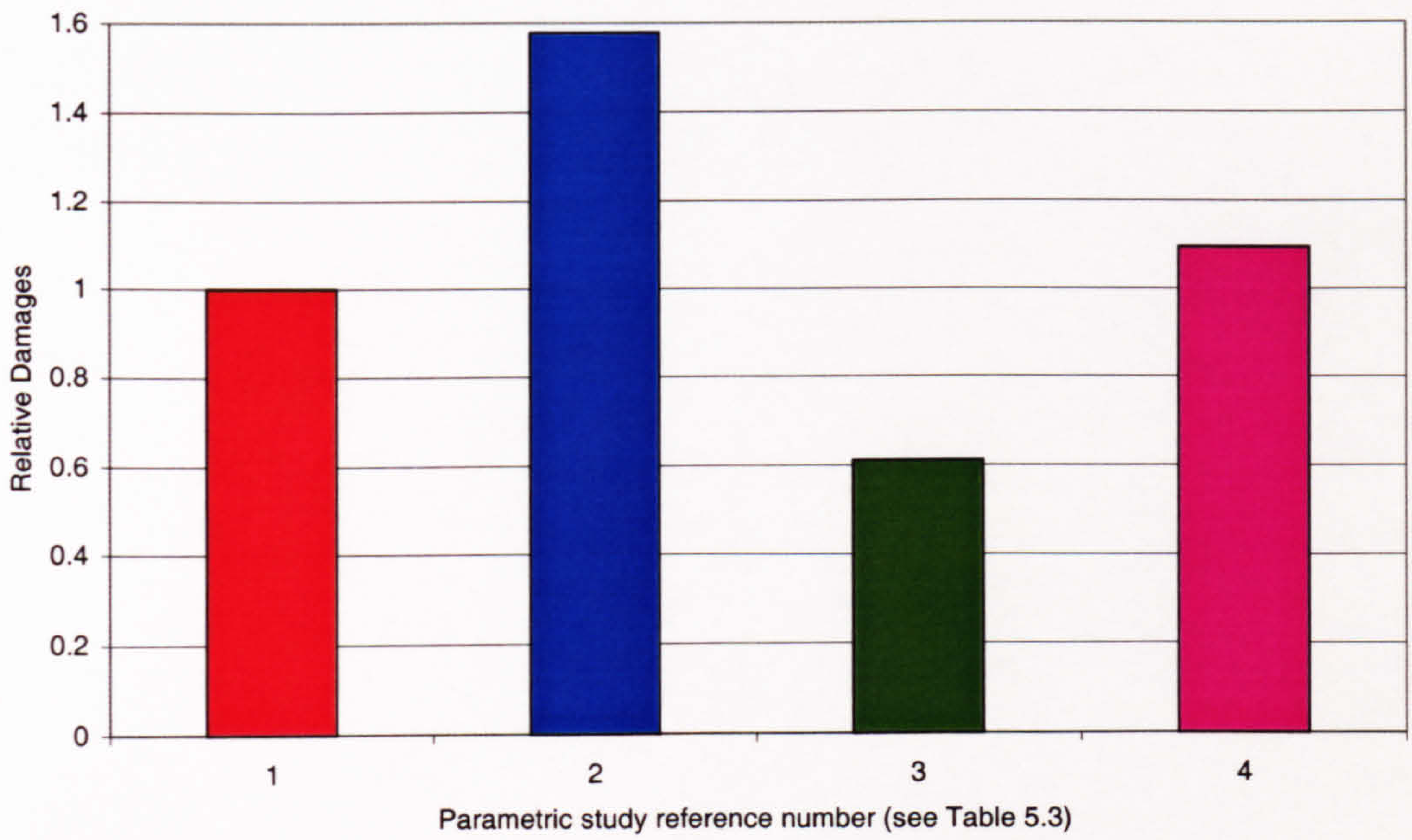


Figure 5.5. Comparison of the normalised total damage results obtained from the parametric studies for the earthquake magnitude

5.1.3 Local Geology, Attenuation Equations, Building Vulnerability and Population Presence

5.1.3.1 Introduction

In addition to the parametric studies involving the earthquake characteristics further studies concerning the local geology, the attenuation relationships, the vulnerability of the building stock and the population presence were also performed as described below.

5.1.3.2 LOCAL GEOLOGY

From its conceptual stage, the approach followed for the involvement of the geology in the model, was considered as rather crude. The way the geology for each administrative area was identified and assumed uniform, for the whole area of that particular village/town, could by no means be considered as accurate. Microzonation will clearly lead to much more accurate results as regards to individual administrative areas. However, for the purposes of this research since there is a large number of administrative areas the overall variability should make this study less sensitive when dealing with the entire island.

The proposed parametric studies for the geology, which will involve the increase/decrease of the S value (i.e. how each geological formation attenuates the seismic waves) of the geological formations of each village/town, is a means of assessing its real impact to the damage distribution. The original and modified S values are presented in Table 5.4. When the resulting S value was negative it was assumed to be zero. The results of the parametric studies for the geology are presented in Table 5.5 and Figure 5.6.

Table 5.4. Original and proposed S values for each one of the nine geological formations

		Geological Formation								
		1	2	3	4	5	6	7	8	9
1	Original	0	0.75	0.5	0.5	0	1	1	1	1
2	S-0.25	0	0.5	0.25	0.25	0	0.75	0.75	0.75	0.75
3	S+0.25	0.25	1	0.75	0.75	0.25	1.25	1.25	1.25	1.25

Table 5.5. Results of the parametric studies for the geology

	Study	Damages (No of total damaged buildings)	Total Damage Cost (£ Cyprus Pounds)	Fatalities	Injuries
1	Original	24327	£767,814,799	41	342
2	S-0.25	24799	£776,435,661	41	346
3	S+0.25	22829	£723,887,541	39	325
4	Average	23814	£750,161,601	40	336

Overall the geology does not appear to influence the results significantly, even though locally it has a very high effect. The damage cost, fatalities and injuries showed the same slight differences and their corresponding plots are presented in Section 4 of Appendix D.

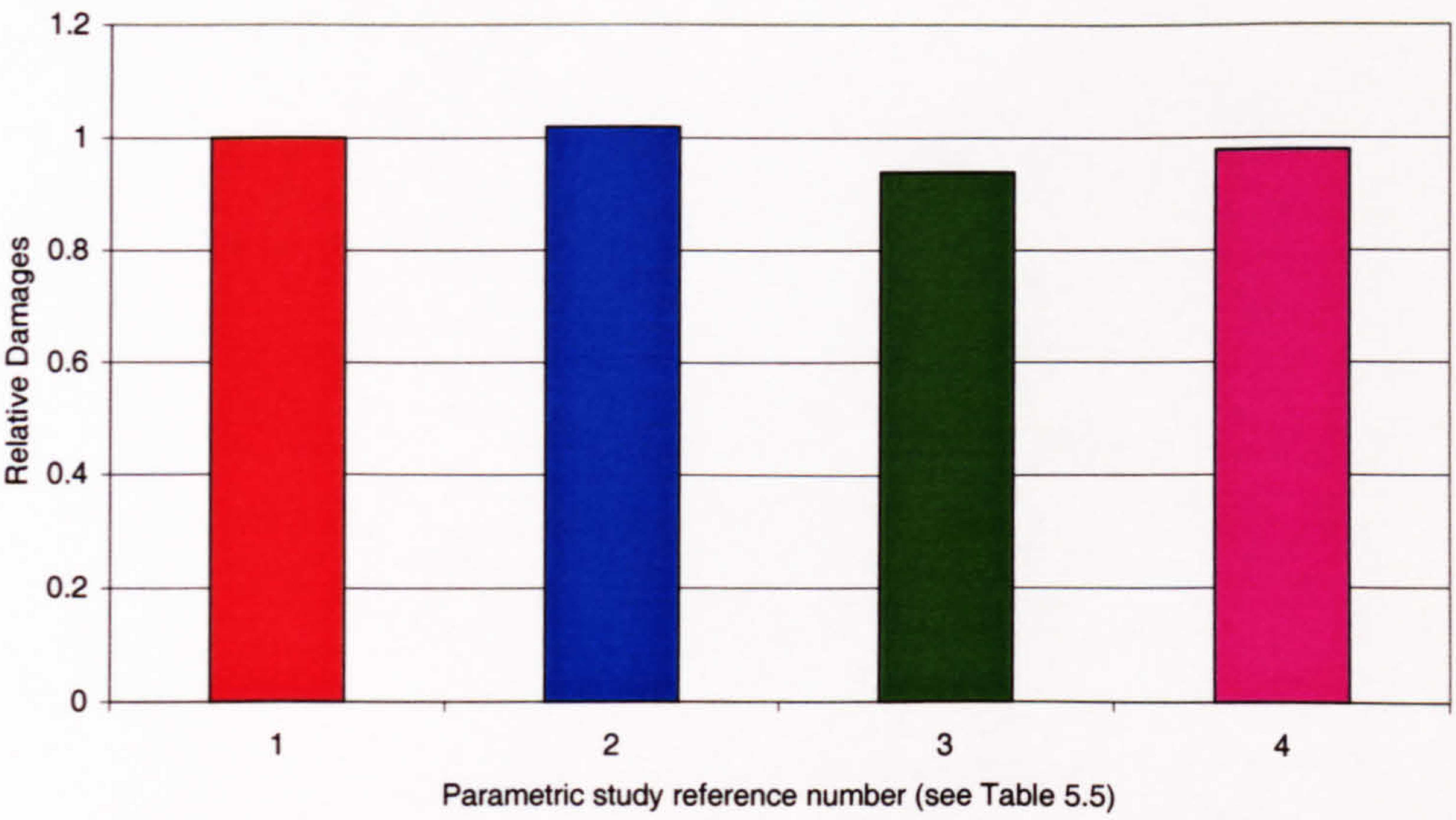


Figure 5.6. Comparison of the normalised total damage results obtained from the parametric studies for the geology

5.1.3.3 ATTENUATION EQUATIONS

During the identification and selection process of the most suitable attenuation equation for the PGA and I_{MM}, the complexity of their various parameters involved became apparent. Details on the selection process were presented in chapter 3. At that stage the need for further particular studies was identified. It was therefore decided to perform parametric studies involving the selected attenuation relations (equations 3a, 3b - Section 2.1 - Appendix B; and equation 3.6) derived by Theodulidis and Papazachos (1992).

The parametric studies suggested, involved the variation of the parameter P representing the statistical variability. Since P is equal to zero for 50 percentile values and equal to one for 84 percentile values, it was decided to find the value of P for different percentiles based on a normal distribution. The parameters are presented in Table 5.6 and the results in Table 5.7, Figure 5.7 as well as in Section 5 of Appendix D.

Table 5.6. Input P values for specific percentiles

Study	P	%	Equation 3a	Equation 3b	Equation 3.6
1	0	50%	-	-	-
2	1	84%	0.71	0.66	0.59
3	-1	16%	-0.71	-0.66	-0.59
4	1.65	95%	1.1715	1.089	0.9735
5	-1.65	5%	-1.1715	-1.089	-0.9735

The trend of the results obtained from the five parametric studies was predictable, with increasing damage as attenuation is reduced.

Table 5.7. Results of the parametric studies for the attenuation equations

Study	P	Damages (No of total damaged buildings)	Total Damage Cost (£ Cyprus Pounds)	Fatalities	Injuries
1	0	24327	£767,814,799	41	342
2	1	32251	£1,019,933,756	62	475
3	-1	17924	£563,094,914	29	250
4	1.65	38590	£1,225,285,987	82	594
5	-1.65	14396	£450,818,887	22	197

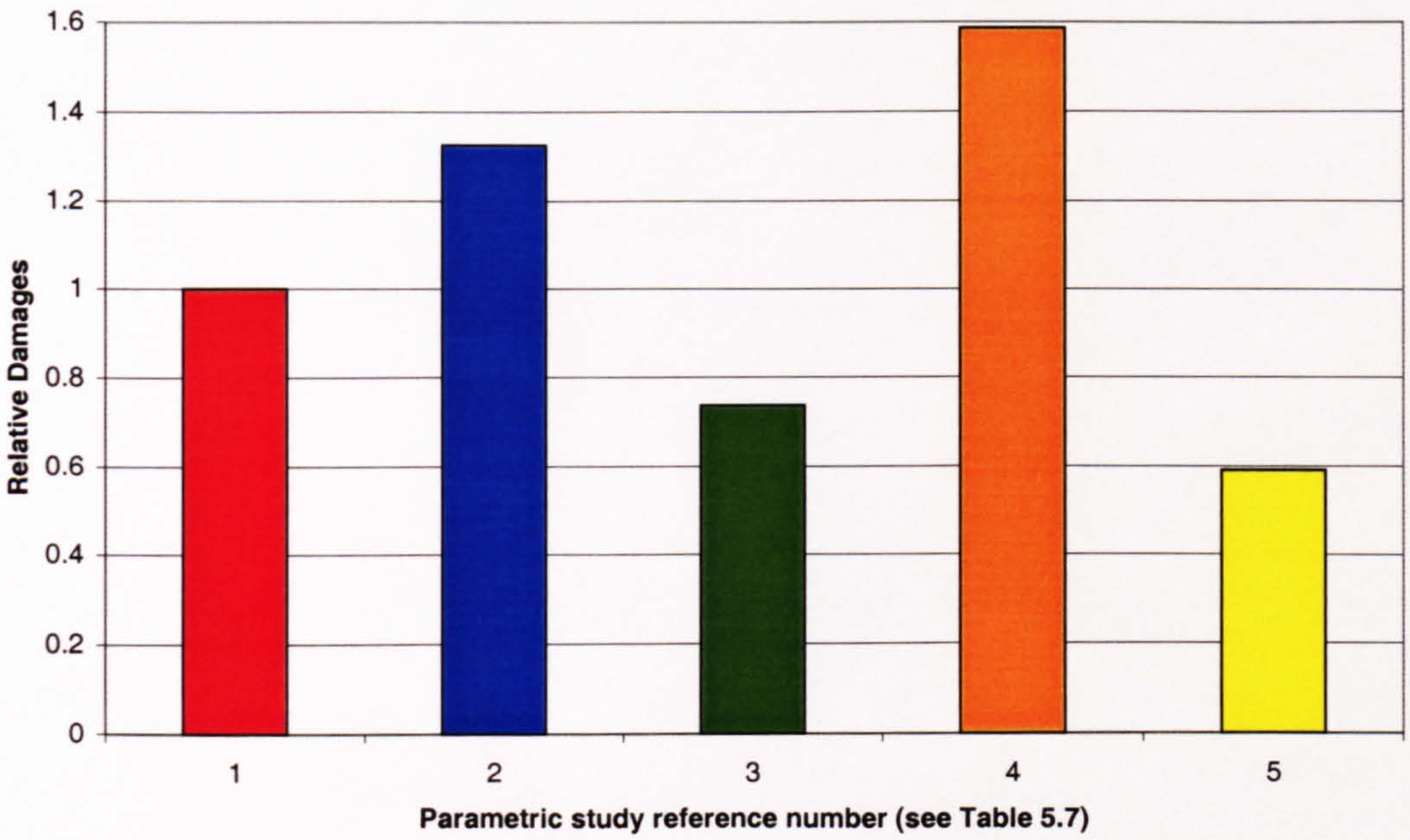


Figure 5.7. Comparison of the normalised total damage results obtained from the parametric studies for the attenuation equations

5.1.3.4 VULNERABILITY OF BUILDING STOCK

The involvement of the vulnerability of buildings in the model was achieved with the introduction of the mean damage ratios first suggested by Schnabel (1987). The values adopted were adjusted accordingly and the initial results obtained were verified with the real damage results of various earthquakes. Despite the fact that the selected input MDRs gave satisfactory results a parametric study with further readjustments to the values was performed for a better understanding of the impact of vulnerability on the damage distribution for all structural, economic and human losses.

Two different approaches (Study I and Study II) were developed and examined. The first (Study I) involved the increase and decrease of all the MDRs by a constant amount ±10% and ±20% of the MDR for I = X (Figure 5.8). The second (Study II) involved the uniform increase/decrease of all the MDRs by a factor of ±20% (Figure 5.9). As with the previous parametric studies the resulting negative input values were taken as zero. Tables of the MDR used for each individual parametric study are included in Section 6 of Appendix D.

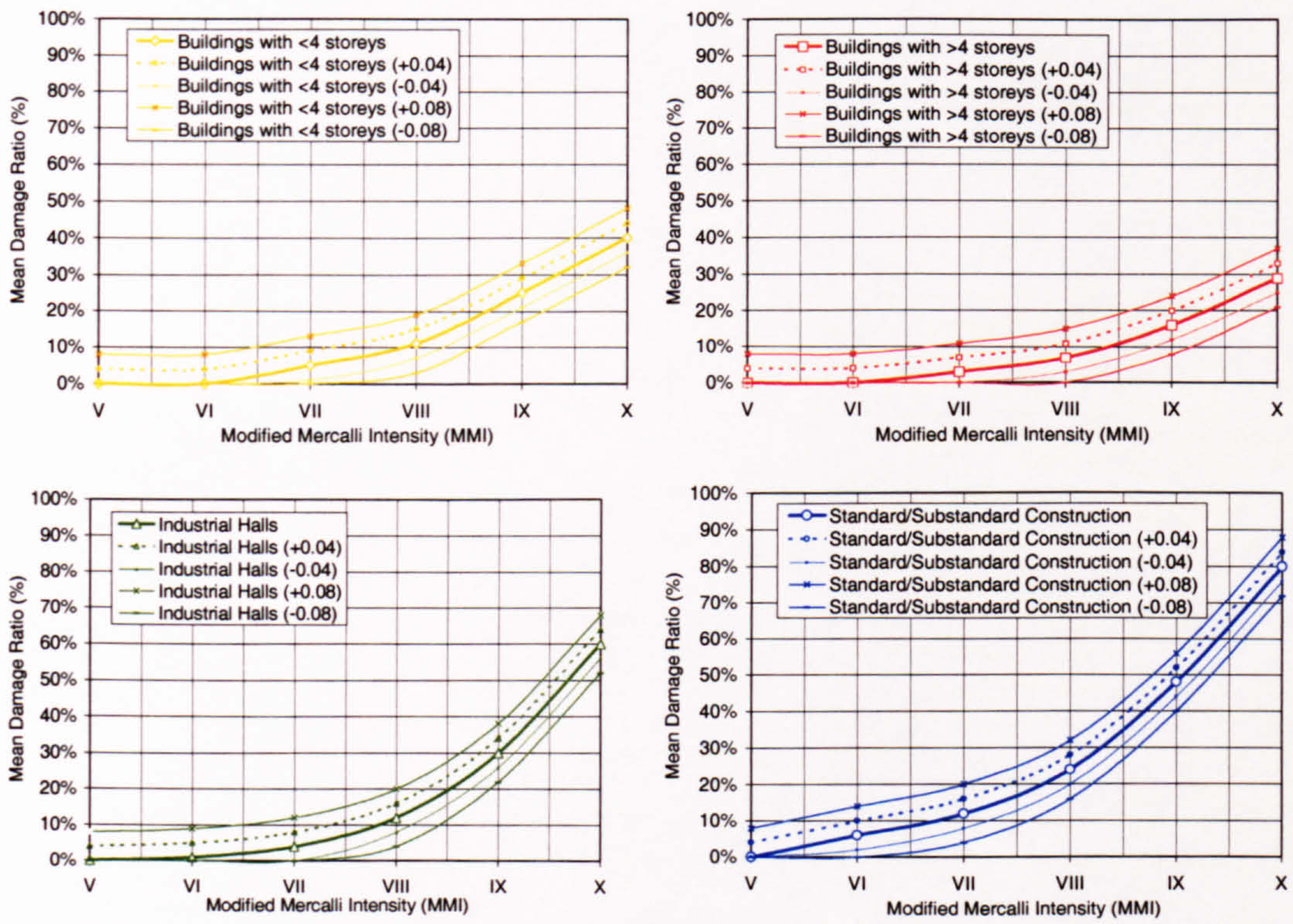


Figure 5.8. Mean Damage Ratios with increase and decrease of ±10% and ±20% of the MDR for I = X for the superior construction < 4 storeys buildings (Study I)

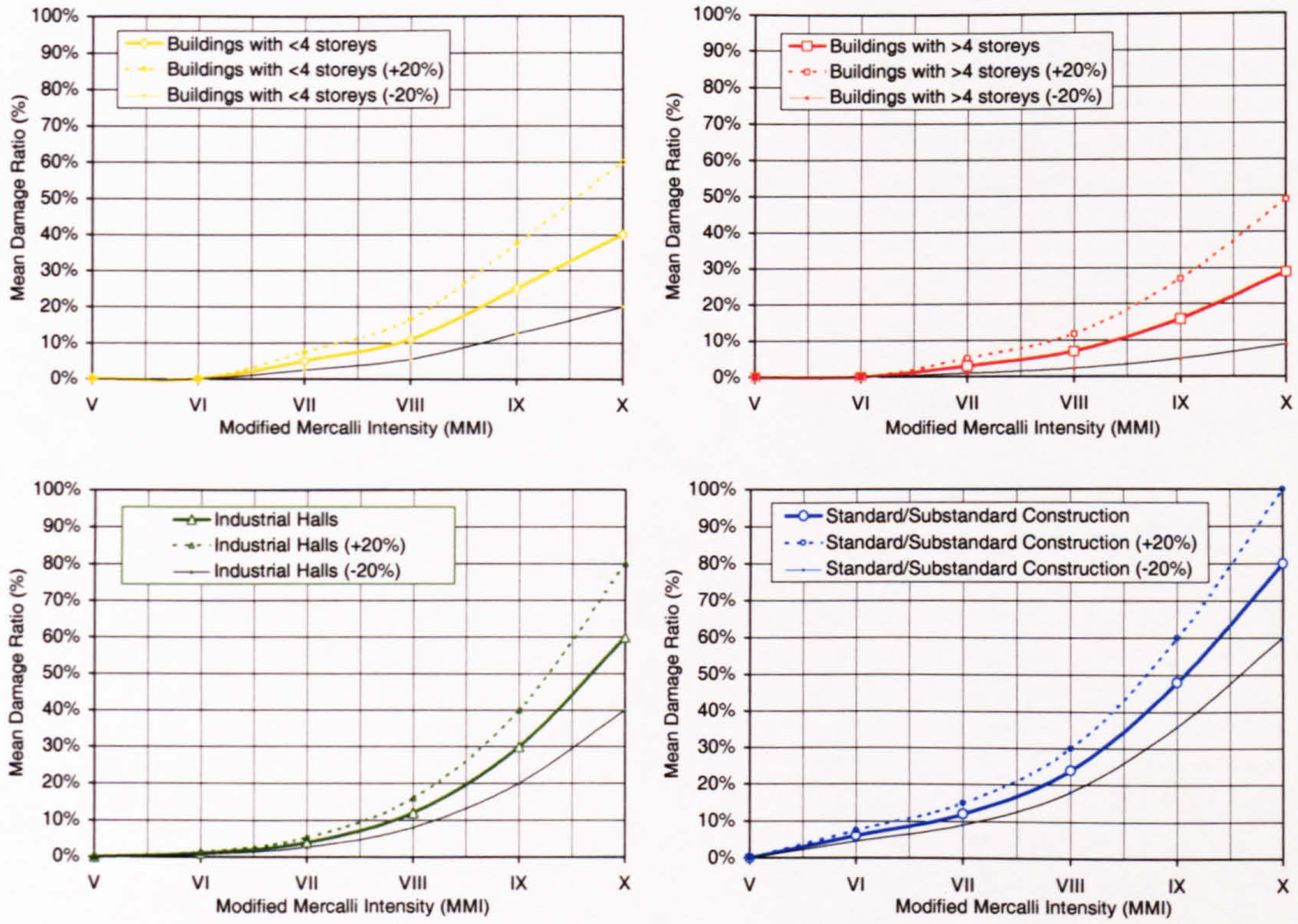


Figure 5.9. Mean Damage Ratios with uniform increase/decrease by ±20% (Study II)

The results for Study I are shown in Table 5.8, Figure 5.10 and in Section 6.1 of Appendix D. A predictable pattern is observed but the magnitude of the increase or decrease on damage is massive. This indicates that the vulnerability is one of the key issues in risk determination. However, the change of one intensity scale appears to have a very high effect on the overall cost of earthquakes.

Table 5.8. Results of the parametric studies for the vulnerability (Study I)

Study			**Damages** (No of total damaged buildings)	**Total Damage Cost** (£ Cyprus Pounds)
1	Original		24327	£767,814,799
2	plus 10%	+0.04	71470	£3,057,396,071
3	minus 10%	-0.04	8748	£260,908,763
4	plus 20%	+0.08	118613	£5,346,977,343
5	minus 20%	-0.08	1108	£32,913,642

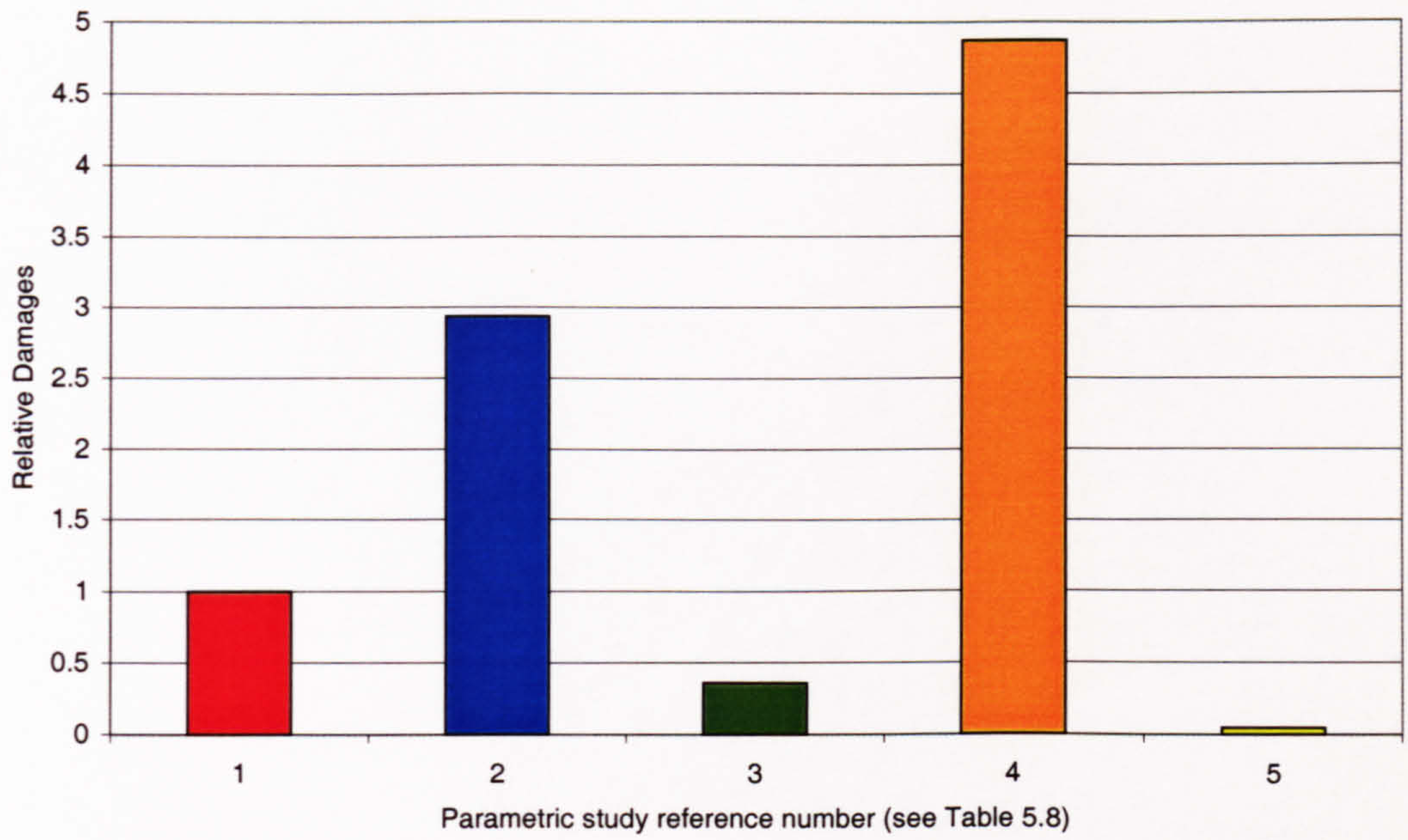


Figure 5.10. Comparison of the normalised total damage results obtained from the parametric studies for the vulnerability (Study I)

The results of Study II are presented and illustrated in Table 5.9, Figure 5.11 as well as in Section 6.2 of Appendix D. The same pattern is observed for Study II but the magnitude of the change is much smaller. This approach appears to be much more sensible since the errors implied are more likely than the ones of study I.

Table 5.9. Results of the parametric studies for the vulnerability (Study II)

	Study	Damages (No of total damaged buildings)	Total Damage Cost (£ Cyprus Pounds)
1	Original	24327	£767,814,799
2	plus 20%	31198	£1,104,313,287
3	minus 20%	17499	£596,605,590
4	Average	24349	£850,459,439

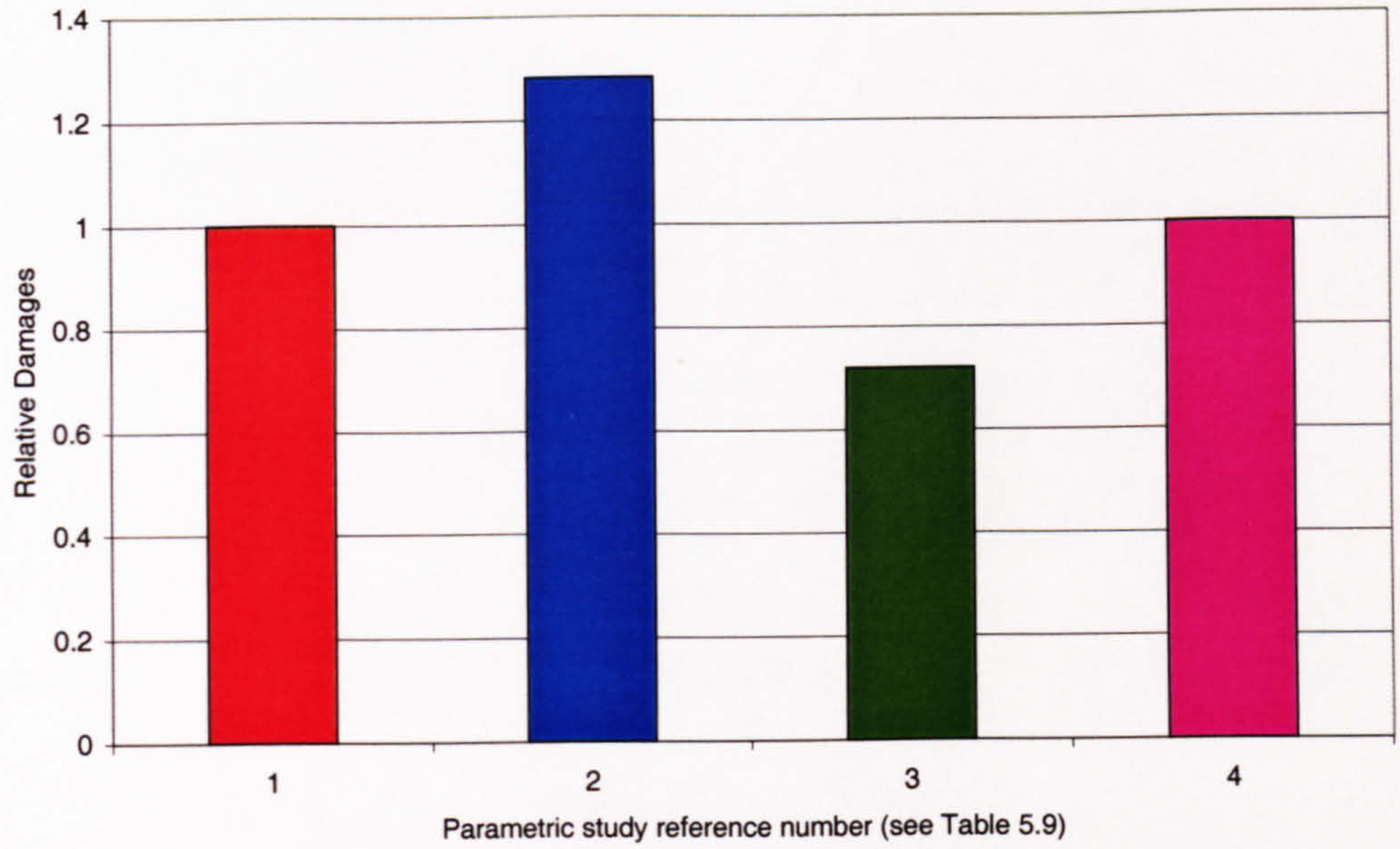


Figure 5.11. Comparison of the normalised total damage results obtained from the parametric studies for the vulnerability (Study II)

5.1.3.5 POPULATION PRESENCE

The population distribution was obtained from the 1992 Census of Population of the Department of Statistics of Cyprus. However, the actual presence during day and night hours was decided based on observations and personal experience of the lifestyle and living patterns of the people of Cyprus.

The original and modified population presence percentages are listed in Table 5.10. An attempt is made to reflect extremes in the likely location of the population.

Table 5.10. Original and proposed population presence percentages (%)

%	Location	Summer Day 7am-10pm	Summer Night 11pm-6am	Winter Day 8am-7pm	Winter Night 8pm-7am
1	Home	20%	70%	25%	80%
	Public	20%	0%	25%	0%
	Private	20%	20%	25%	15%
	Outdoors	40%	10%	25%	5%
2	Home	70%	25%	80%	20%
	Public	0%	25%	0%	20%
	Private	20%	25%	15%	20%
	Outdoors	10%	25%	5%	40%
3	Home	25%	80%	20%	70%
	Public	25%	0%	20%	0%
	Private	25%	15%	20%	20%
	Outdoors	25%	5%	40%	10%
4	Home	80%	20%	70%	25%
	Public	0%	20%	0%	25%
	Private	15%	20%	20%	25%
	Outdoors	5%	40%	10%	25%

In contrast to the studies involving the vulnerability of the buildings, the studies performed for the population presence demonstrated that overall this parameter does not influence the results significantly (i.e. fatalities and injuries) as to consider it of "great" importance. This is presented clearly in Figure 5.12 and Figure 5.13 of the total normalised fatalities and injuries. Again the results are predictable with more deaths and injuries as the population in buildings increases.

Table 5.11. Results of the parametric studies for the population presence

	Study	Fatalities	Injuries
1	Original	41	342
2	plus 20%	37	333
3	minus 20%	41	343
4	Average	38	340

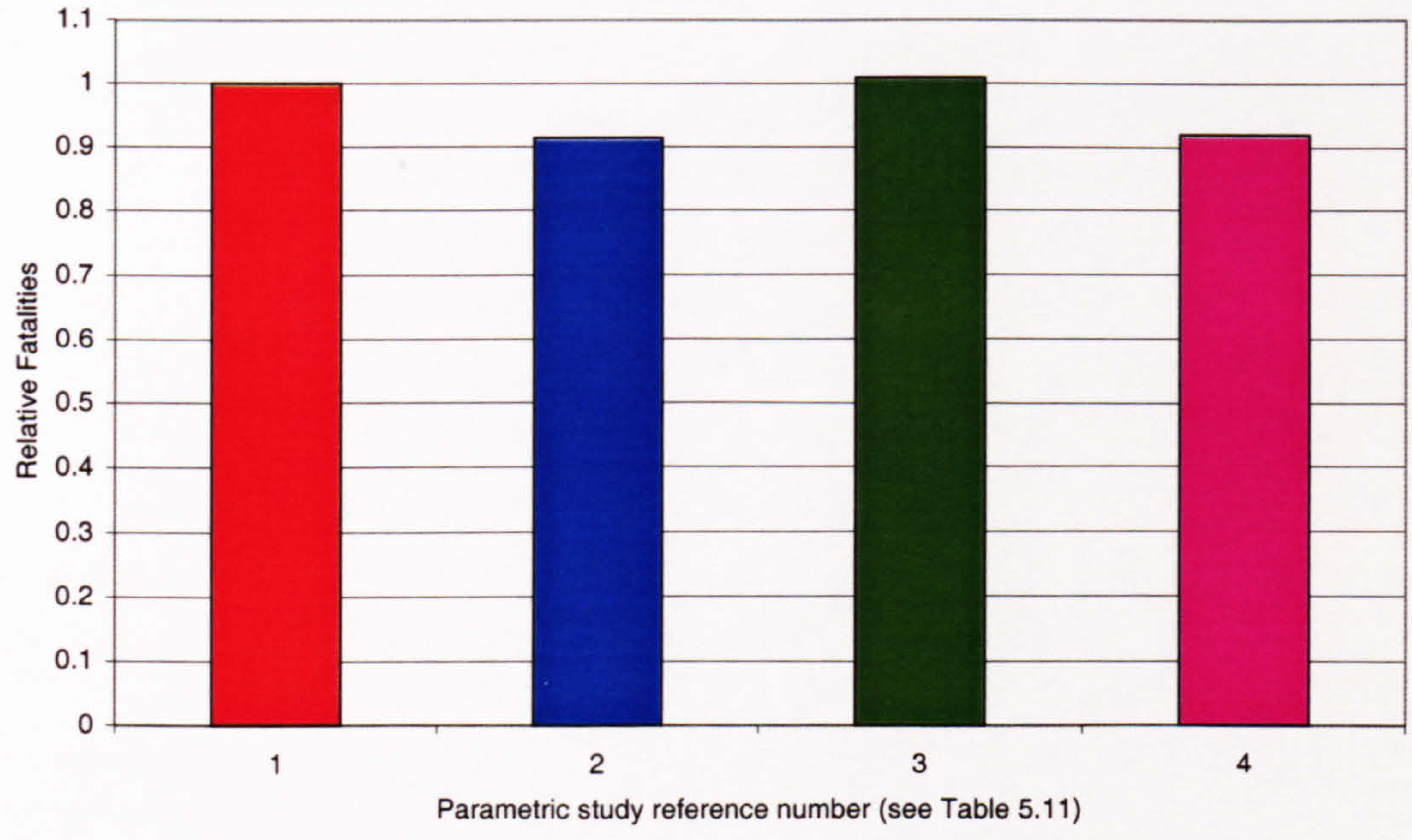


Figure 5.12. Comparison of the normalised total fatalities results obtained from the parametric studies for the population presence

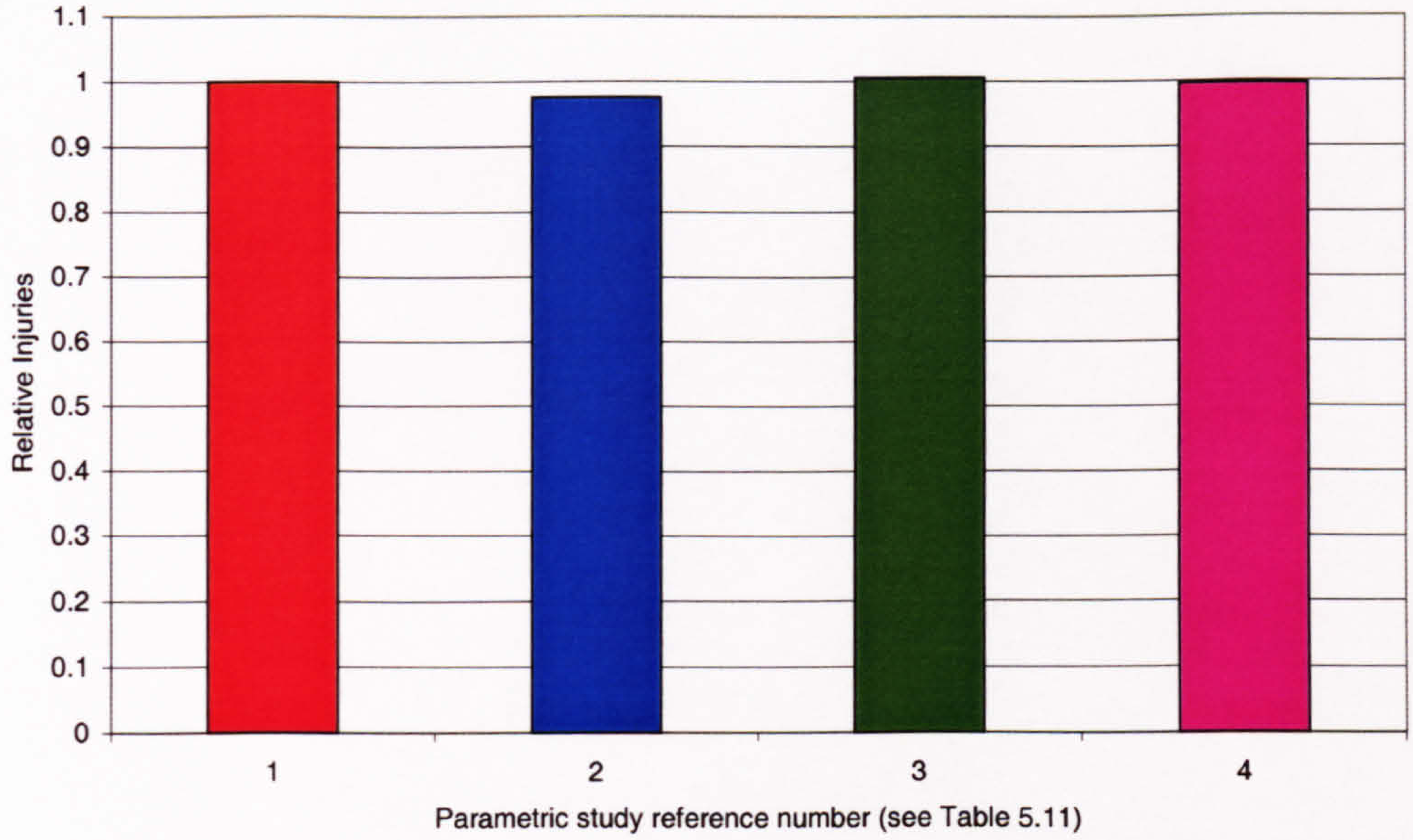


Figure 5.13. Comparison of the normalised total injuries results obtained from the parametric studies for the population presence

5.1.4 CONCLUSIONS

The parametric investigation of risk proved to be useful in identifying the parameters that influence its assessment. Based on the feedback from the various parametric studies the following section will identify the parameters which significantly affect the results and determine the procedure that would be followed for the probabilistic inclusion of these variables in the ERA.

5.2 VARIABILITY OF PARAMETERS

During the parametric investigation of risk it was noticed that not all of the parameters affected the results in a significant manner. For example the location of people during the earthquake did not influence the results significantly and, therefore, its random modification was considered unnecessary. However, there were other parameters which affected the results in a non-linear manner.

Before proceeding with further simulations, the attenuation equations were used to examine whether they were responsible for this result. The parameter P (which is zero for 50 percentile values and one for 84 percentile values) was assigned three values –1, 0 and +1 and the equation (3a) was solved for different magnitudes, with the depth (R) taken equal to zero, and for both S equal to zero and one. The average of the results obtained for P=-1 and P=1 were found to be more or less equal to the results when P=0 (Figure 5.14, Figure 5.15). It was therefore concluded that the increase in risk is due to non-linearity of the magnitude and depth parameters.

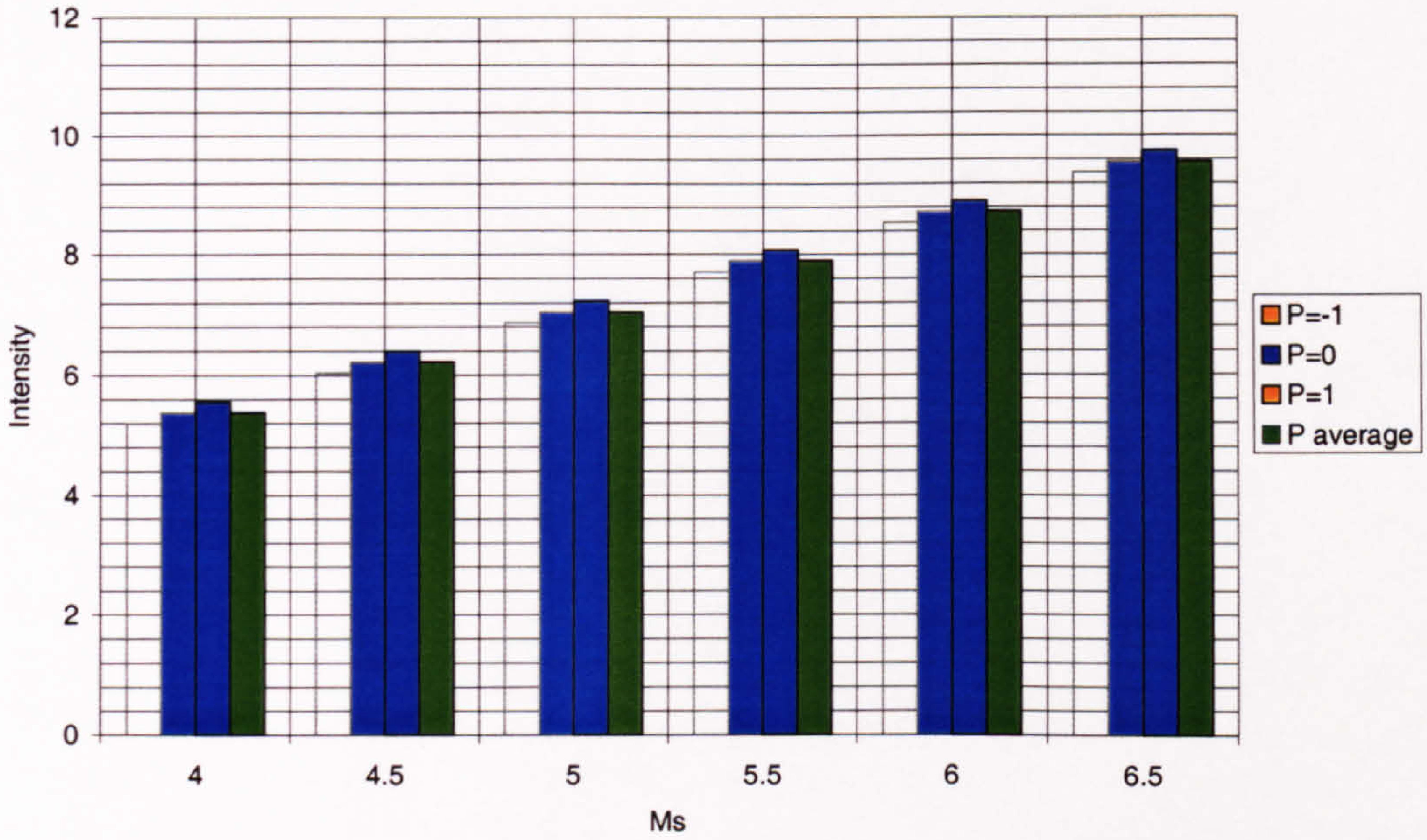


Figure 5.14. S=1 for P=-1, P=0, and P=1

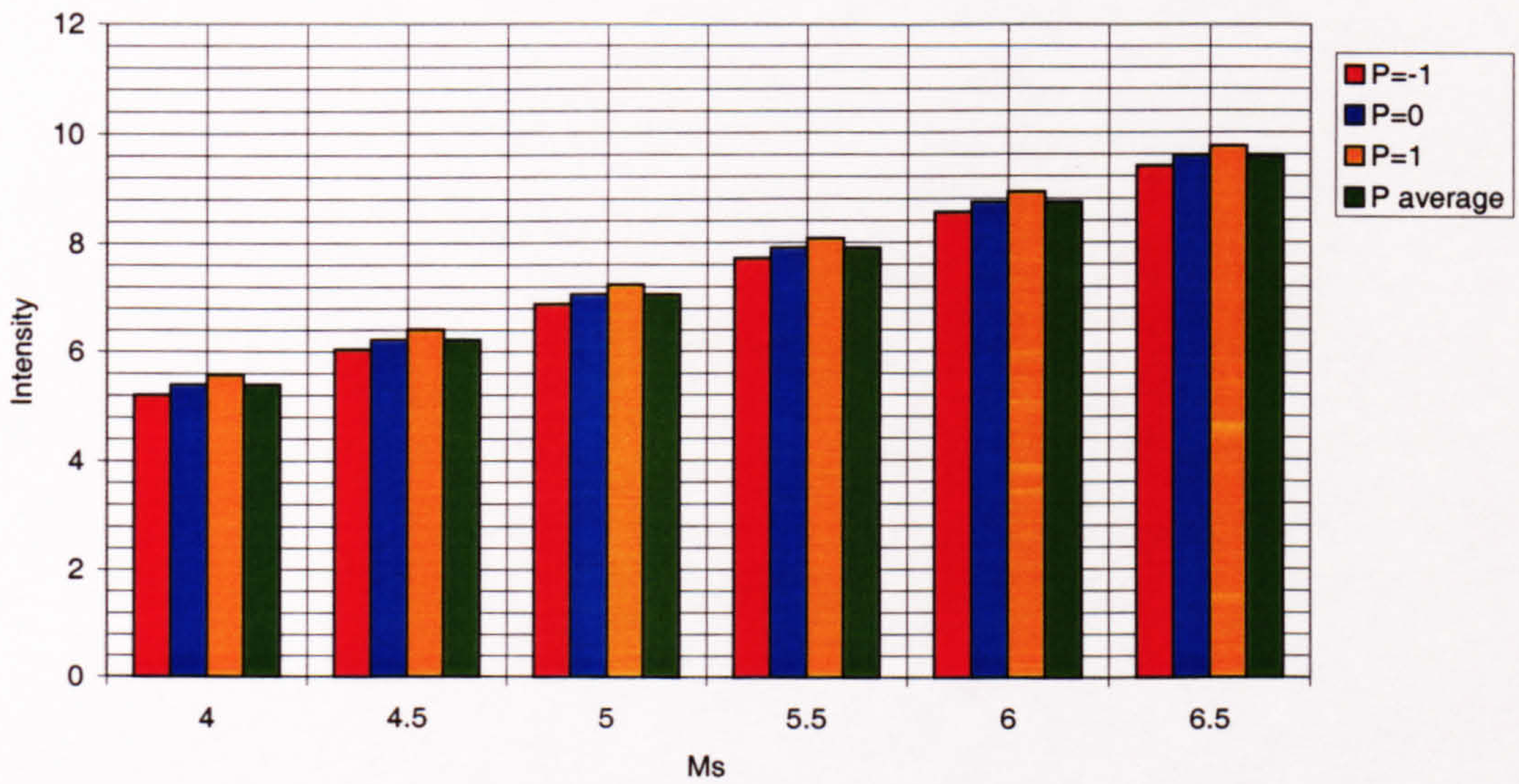


Figure 5.15. S=0 for P=-1, P=0, and P=1

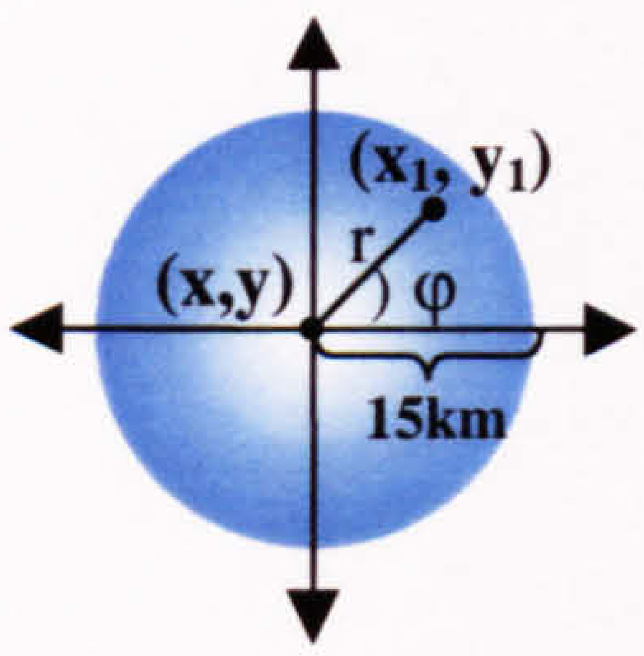
In Table 5.12 the limits of the random numbers generated for the various parameters affecting the results, will be presented, the way their modification was selected will also be explained in the following sections.

Table 5.12. Limits of random numbers generated for each individual parameter

Parameter	Ranges	Distribution
Epicentres	0km to 15km	Uniform
	0° to 360°	Uniform
Depth	-20km to +20km	Uniform
Magnitude	-0.2 to +0.2	Uniform
Geology	-0.25 to +0.25	Uniform
P value	N/A	Normal
MDRs	max to min	Uniform
MFRs - MIRs	No randomness	N/A

5.2.1 EPICENTRES

The uncertainty in the epicentral location was simulated by a more or less uniform distribution within an area of 15km radius (Papaioannou, 2000). For each event a distance (r) between 0 and 15km as well as an angle (φ) between 0° and 360° are randomly generated with equal probability, this implies that the spatial probability distribution is proportional to the square root (r^2) from the epicentre. A new set of co-ordinates is then calculated based on simple trigonometric rules (Figure 5.16).



$$x_1 = x + r\cos\varphi$$
$$y_1 = y + r\sin\varphi$$

Figure 5.16. Set of equations used for the generation of the new sets of the earthquake co-ordinates

5.2.2 DEPTH

Papaioannou (2000) suggested that the variation of depth should also be based on a uniform probability. A value between -20 to +20 km was randomly generated based on a uniform distribution and added to the original value of the depth. If the resulting value was negative (i.e. above ground level) then the depth was assumed to be equal to zero.

5.2.3 MAGNITUDE

The magnitudes of the earthquakes were also generated randomly based on a uniform probability. The random values generated and added to the original magnitudes were between -0.2 and +0.2.

5.2.4 GEOLOGY

The geology is involved in the simulations through the modification of the S value. A randomly generated value, based on a uniform probability, between -0.25 and +0.25 is added to the original S value. If the resulting number is less than zero it is assumed to be zero and if the number is more than one is assumed to be equal to one.

5.2.5 ATTENUATION OF SEISMIC WAVES

For the P value, (representing statistical variability in the attenuation equations) the procedure followed, is exactly the same as the one used for the S values for the geology. However, instead of using uniform distribution, the P value is randomly generated based on a normal distribution and the standard deviation (σ) given by Theodulidis and Papazachos (1992) for the equation. This is repeated for each village and each earthquake.

A test was performed to check whether there is any non-conformity between the various relationships derived by Theodulidis and Papazachos (1992). The results (Figure 5.17) showed that the attenuation equations (particularly the one for the acceleration) are not really suitable, since they cannot be combined (i.e. they can not be used to go from M_S to I_{MM}). By using them in that way the geology effect disappears.

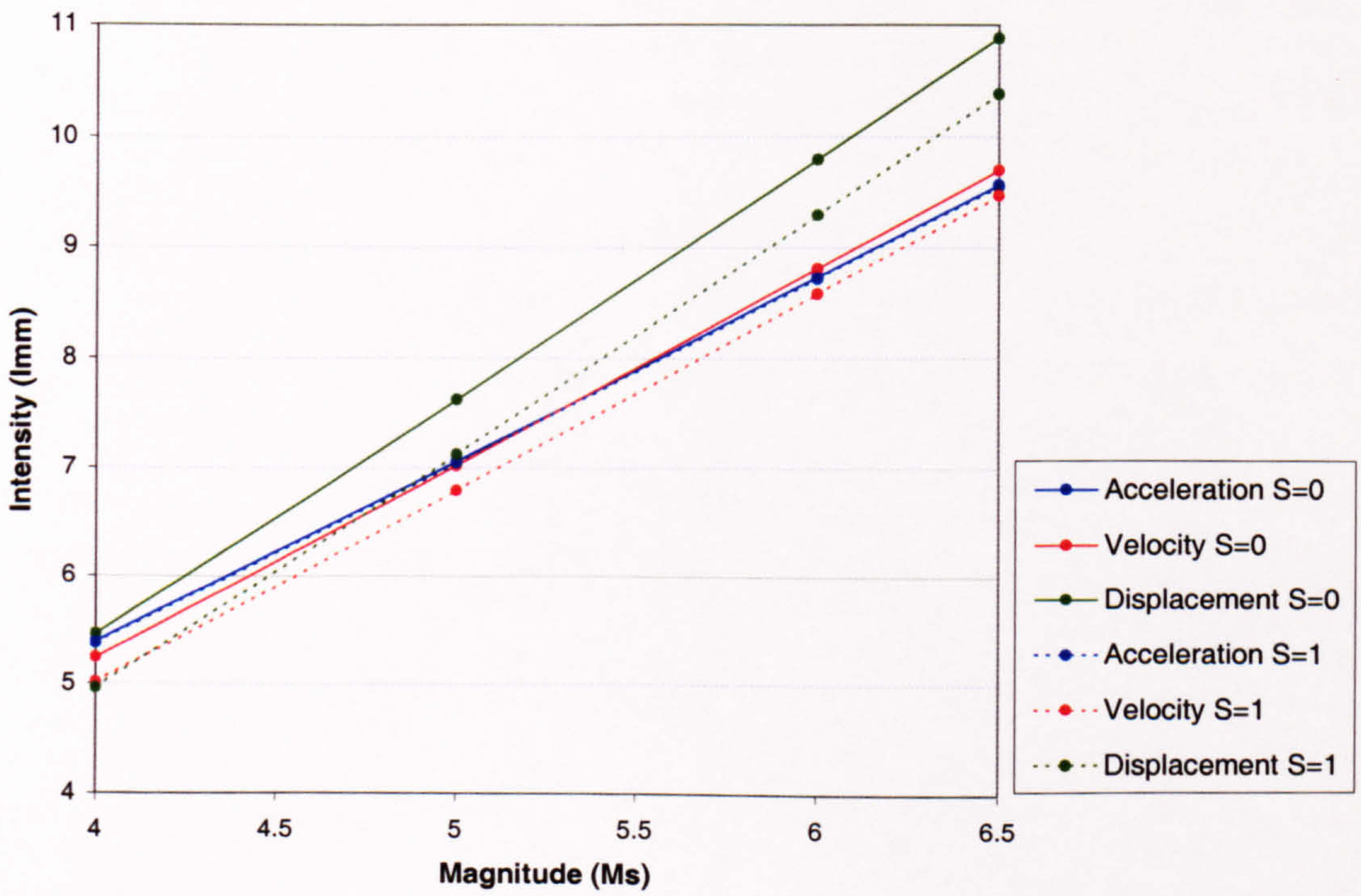


Figure 5.17. Comparison of Theodulidis and Papazachos relationships for S equal to one and zero, using epicentral distances (R) and P equal to zero

However, because the effect of the P value is to a significant extend determined by the intermediate geology as well as the local geology, it will be assumed that either directly or indirectly the P value is affected by the geology.

5.2.6 VULNERABILITY – MDR$_S$

As part of the parametric investigation of the risk the MDRs were increased and decreased by 20%. The maximum and minimum values for each separate intensity and each building type were identified and a random real number was then generated between these maximum and minimum values. For each area and for every new earthquake a new MDR value is generated and used.

5.2.7 FATALITIES - MFR$_S$ AND INJURIES - MIR$_S$

For the purposes of this study the MFRs and the MIRs have not been randomly generated since they do not affect the economic risk. However, their random generation could be studied and applied at a later stage.

5.3 DISCUSSION

The parametric studies identified all the parameters which significantly affect the assessment of the earthquake risk. The ranges and limits of each important parameter were selected for use at the next stage of probabilistic assessment.

Due to the large number of variables / equations used and limits imposed on these equations a closed form probabilistic estimation of risk is impossible. Hence, a numerical probabilistic approach based on the Monte Carlo simulation technique will be used.

GENERAL DISCUSSION
&
RISK MANAGEMENT STRATEGIES

6.1 INTRODUCTION

Chapter 5 identified the parameters that significantly affect the results of ERA and determined their range of variability. This chapter will assess the effect of this variability on the result of the earthquake risk probabilistically, by using values for these parameters selected through the Monte Carlo technique.

Two hazard determination approaches are proposed and tested for their applicability in the assessment of the earthquake risk. Finally, several RMS are discussed.

6.2 PROBABILISTIC ASSESSMENT OF THE ERA PARAMETER VARIABILITY

6.2.1 MONTE CARLO SIMULATIONS

The values of the ERA parameters used in EQ-RACY were selected randomly by using the Monte Carlo simulation (Kottegoda and Rosso, 1997) approach. This technique uses multiple simulations in which random numbers are used to select particular values from a range of possible values, resulting in a distribution of potential outcomes (Kottegoda and Rosso, 1997).

Table 5.12 shows the parameters, their corresponding ranges and probability distributions, used in each simulation. Each simulation generates randomly new epicentres, depths and magnitudes for the original earthquakes, by combining the randomly generated values to the original values. For each earthquake at each location, new S-value, P-value and MDRs are also randomly selected as described above. Since the time of occurrence of each event is known fairly accurately (within a few seconds) this parameter was not a variable in these simulations.

A sufficient number of simulations is required so that the results can be analysed in a statistical manner and lead to reasonable probabilistic distributions. A total of 100 sets of earthquakes were selected and can be found in the Earthquake cataloques.xls file on the CD of Appendix E. Figure 6.1 presents a comparison between the mean economic value of the earthquake risk over 103 years and the number of individual simulations, starting with a minimum of 6 simulations. The 100 simulations are analysed in sequence of 1-100 and 100-1. It is apparent that the results converge very quickly, with the standard deviation being constant after about 40 simulations (difference less than 0.5%) and the mean not varying significantly after 12 simulations (less than 6%). Hence, 100 simulations were considered to be a more than adequate number for statistically accurate results. The analysis of the results from the 100 simulations gave the following outputs:

- Seismic (ground shaking) intensity, such as PGA and MMI intensity
- Damaged Buildings
- Damage Costs
- Casualties (number of deaths and injuries)

The output is evaluated and reanalysed in an attempt to identify and suggest various RMS. Various initial questions arose during this research and this section deals with the major task of answering some of these issues.

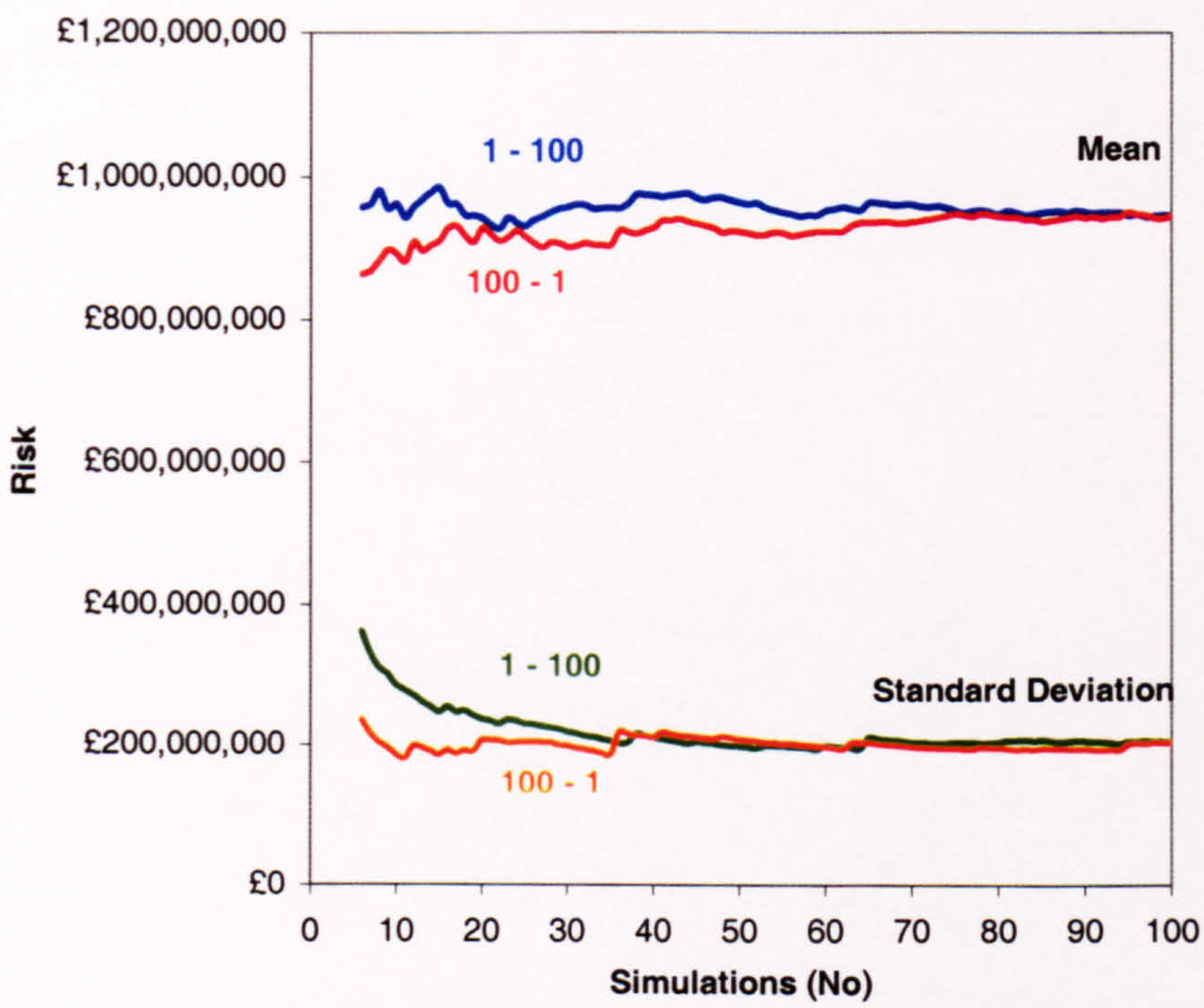


Figure 6.1. Variation in mean and standard deviation of total risk value, as a function of number of simulations

6.2.2 TOTAL EARTHQUAKE RISK, DAMAGES, FATALITIES AND INJURIES FOR THE PERIOD 1894-1997

Figure 6.2 presents distributions of simulation results for the total earthquake risk, damages, fatalities and injuries for the period 1894-1997.

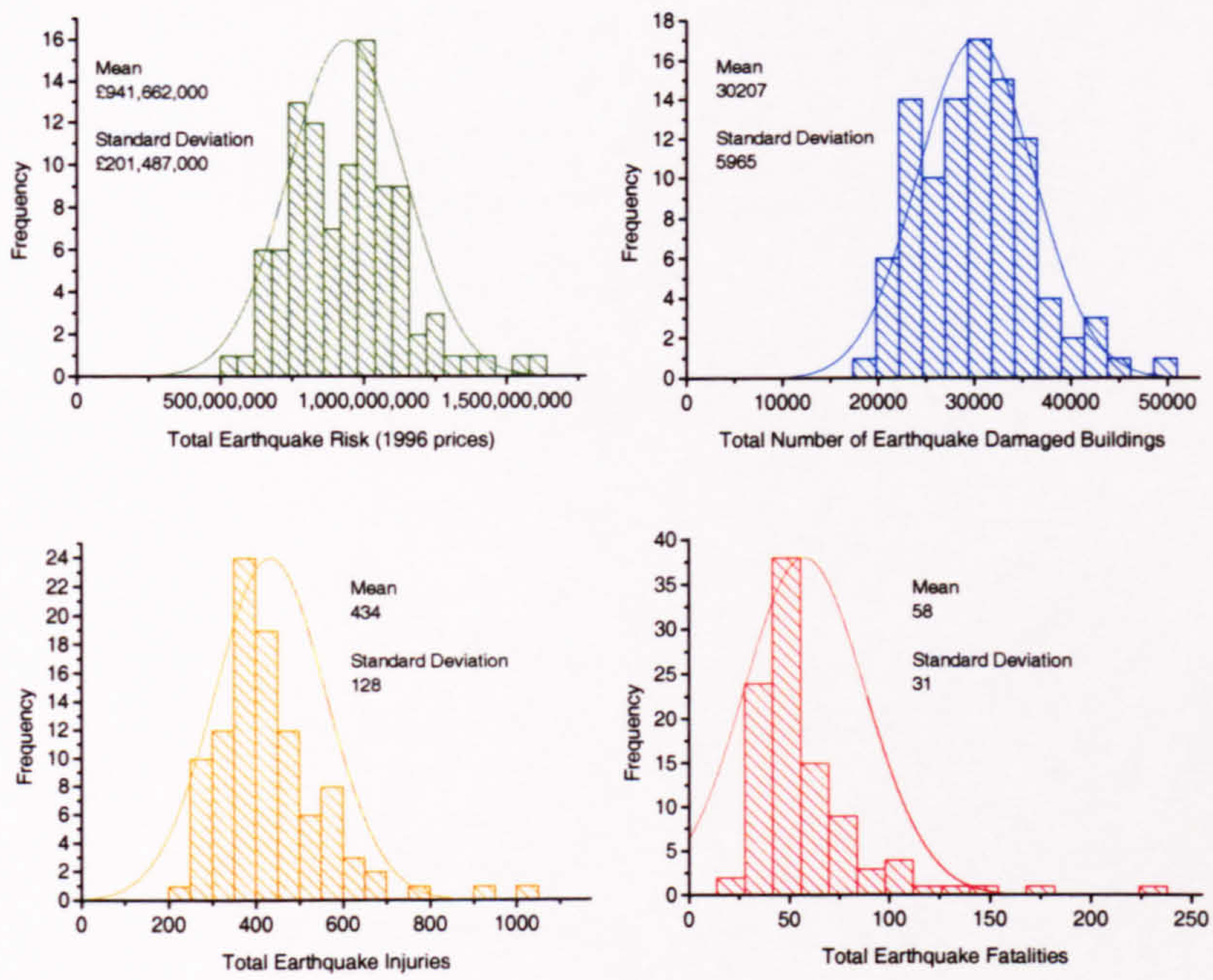


Figure 6.2. Total earthquake risk, damages, fatalities and injuries for a period of 103 years

The mean values are higher than estimated (deterministically) in chapter 5 (Total earthquake risk £767,814,799). For the total earthquake risk the mean value is 23% higher than the obtained previously but still within 1 standard deviation. Bearing in mind the results obtained in the parametric studies of chapter 5, which show that the effect of an increase in most of the parameters is greater than the effect of an equal decrease in the same parameter, the above results are in line with expectations. Despite the high variability of the individual simulation results, the total risk value with probability of exceedance (POE) 5%, which is the normal level of error acceptable for engineering calculations, is £1,274,600,000. This is only 35% higher than the mean, which implies that the values determined by the EQ-RACY model are reasonably accurate for RMS to be based on them.

Normal distributions are fitted to the frequency distributions. The normal distribution appears to be reasonable for the monetary risk, but it is not so good for the injuries and fatalities, which makes the values for the mean and standard deviation less meaningful.

It is unlikely that these values can be used other than for comparison purposes, hence, the risk at the annual level needs to be determined.

6.2.3 AVERAGE ANNUAL EARTHQUAKE RISK, DAMAGES, FATALITIES AND INJURIES

To estimate the average (over a 103 year period) annual earthquake risk, damages, fatalities and injuries, the total values were simply divided by 103 (the period covered by the earthquake catalogue used). Table 6.1 presents the average annual earthquake risk, damages, fatalities and injuries.

Table 6.1. Average annual earthquake risk, damages, fatalities and injuries over a 103 year period

	Mean	Standard Deviation
Earthquake Risk	£9,142,350	£1,956,190
Number of earthquake damaged buildings	293	58
Fatalities	0.56	0.29
Injuries	4.21	1.24

The above indicates that the long term average annual risk is around £10 million CY, which suggests that the government of Cyprus should be allowing for this risk either through insurance or the build up of contingency funds.

6.2.4 AVERAGE ANNUAL EARTHQUAKE RISK PER BUILDING

The average annual earthquake risk per building is estimated by dividing the average annual values with the number of buildings in the island (294563). The long-term average risk per building is £31. This value is very similar to the average insurance rate, as will be discussed in section 6.4.

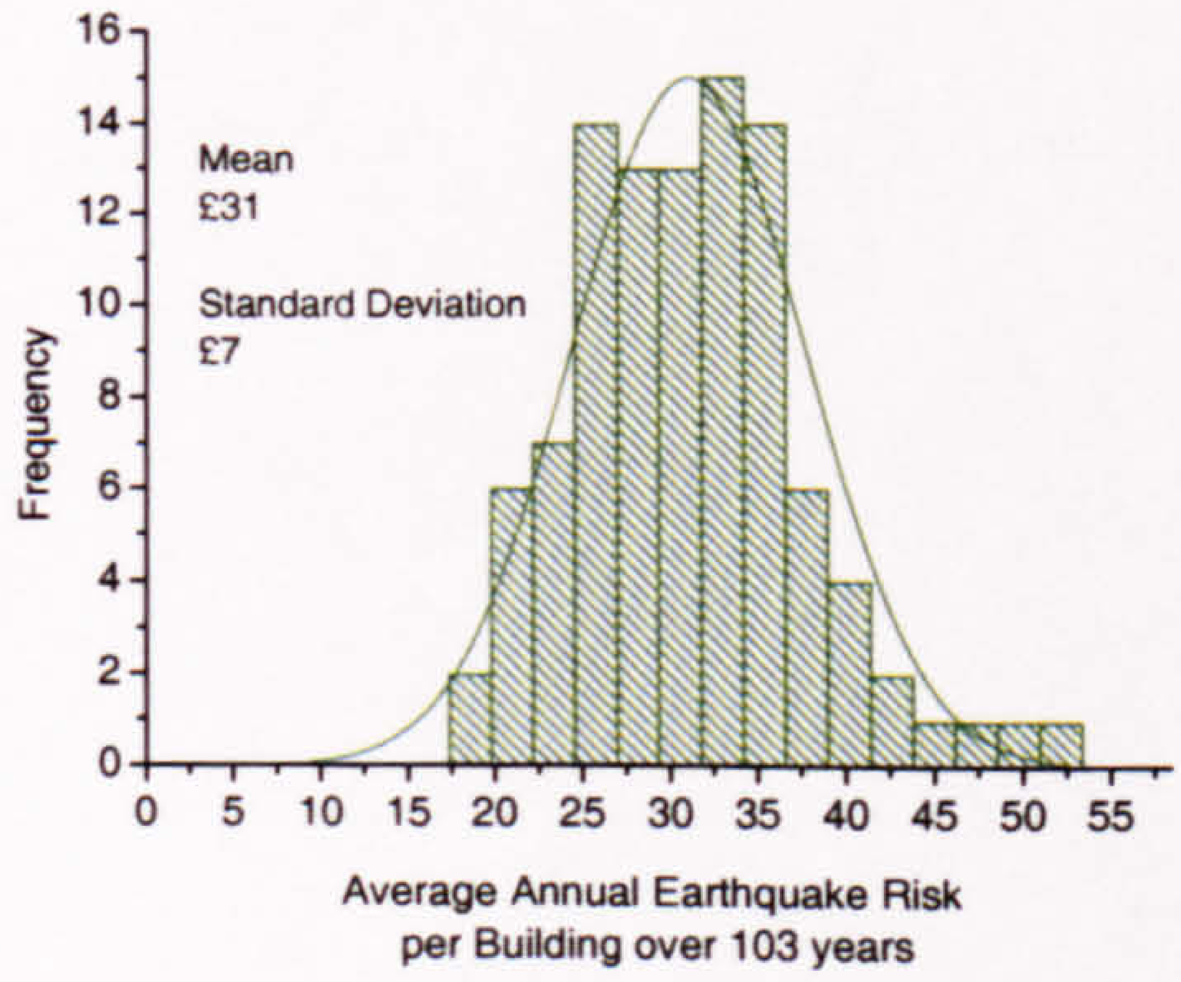


Figure 6.3. Average annual earthquake risk per building over a 103 year period

6.2.5 EARTHQUAKE RISK FOR PERIODS OF 1 YEAR, 10 YEARS, 25 YEARS AND 50 YEARS

The total earthquake risk for a period of 1 year, 10 years, 25 years and 50 years was calculated by adding the annual data of each simulation in tens, twenty-fives and fifties and then calculating the total for each simulation (Figure 6.4). This figure shows the mean, the standard deviation (σ), the POE-5% (95%) and the POE-1% (99%).

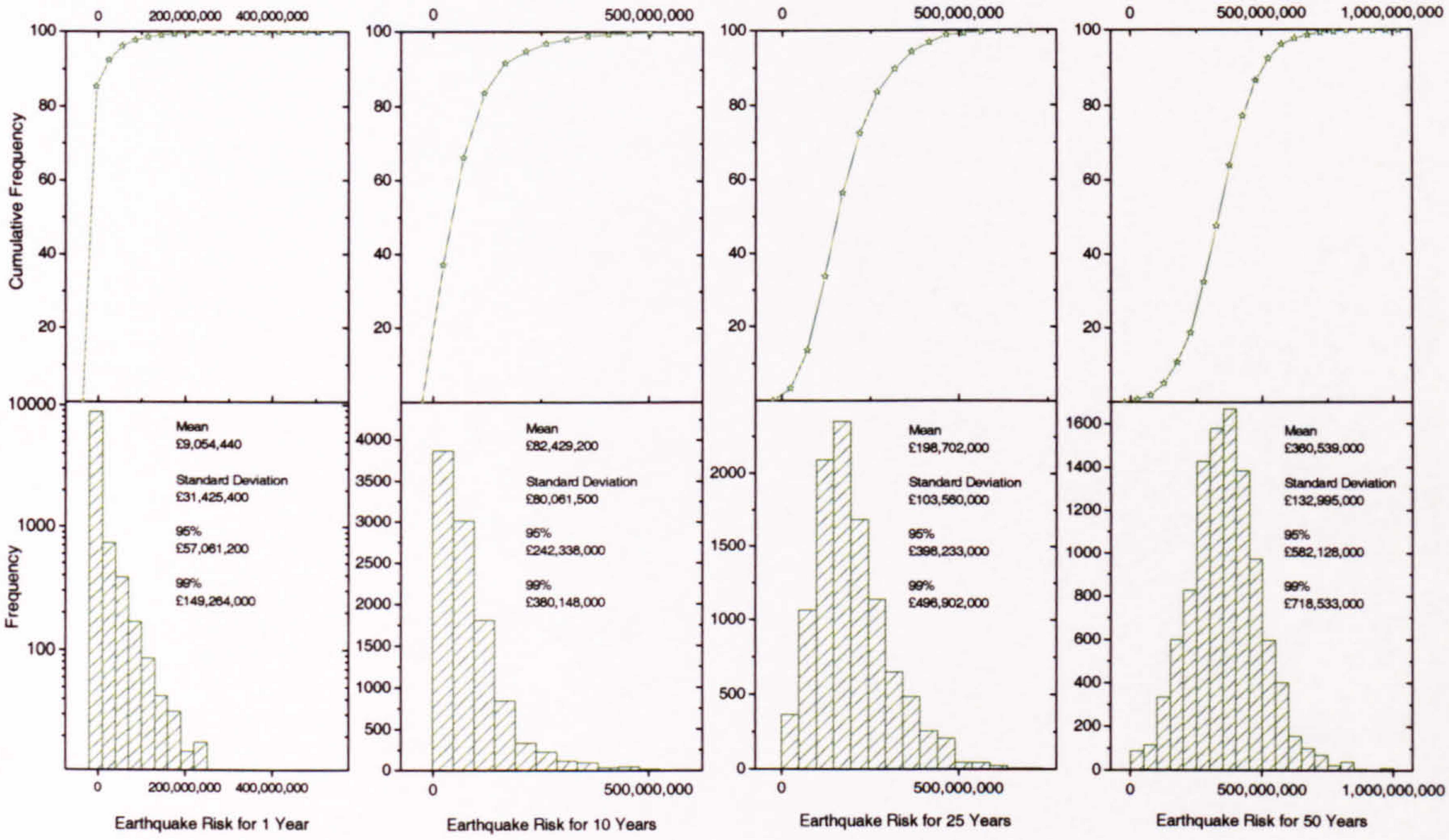


Figure 6.4. The earthquake risk for a period of 1 year, 10 years, 25 years and 50 years

Naturally, as the time period decreases, the number of results increase and hence, the results are more reliable. However, the distribution of the results also changes from a more or less normal distribution (50 years), to a highly skewed distribution towards the low values (1 year or 10 years). Despite these changes the average annual risk does not change by much, being just below £10 million CY. On the contrary, the annual value for POE-5% and POE-1% increase as the time period decreases.

6.2.6 MAX AND AVERAGE FELT INTENSITIES AND ACCELERATIONS

To address the design of new built structures and the possible earthquake hazard they are likely to face during their design life, the maximum as well as the average felt intensities and accelerations need to be examined.

Since 100 simulations were performed, for each area there are 100 maximum intensities and accelerations for the given period (103 years). The maximum and average values of these maximum intensities are shown in Figure 6.5 and Figure 6.6 whilst the corresponding accelerations are shown in Figure 6.7 and Figure 6.8. The maximum values from the 100 simulations can be considered to be extreme values, whilst the average of the 100 simulations is the value to be expected over that period of time (103 years).

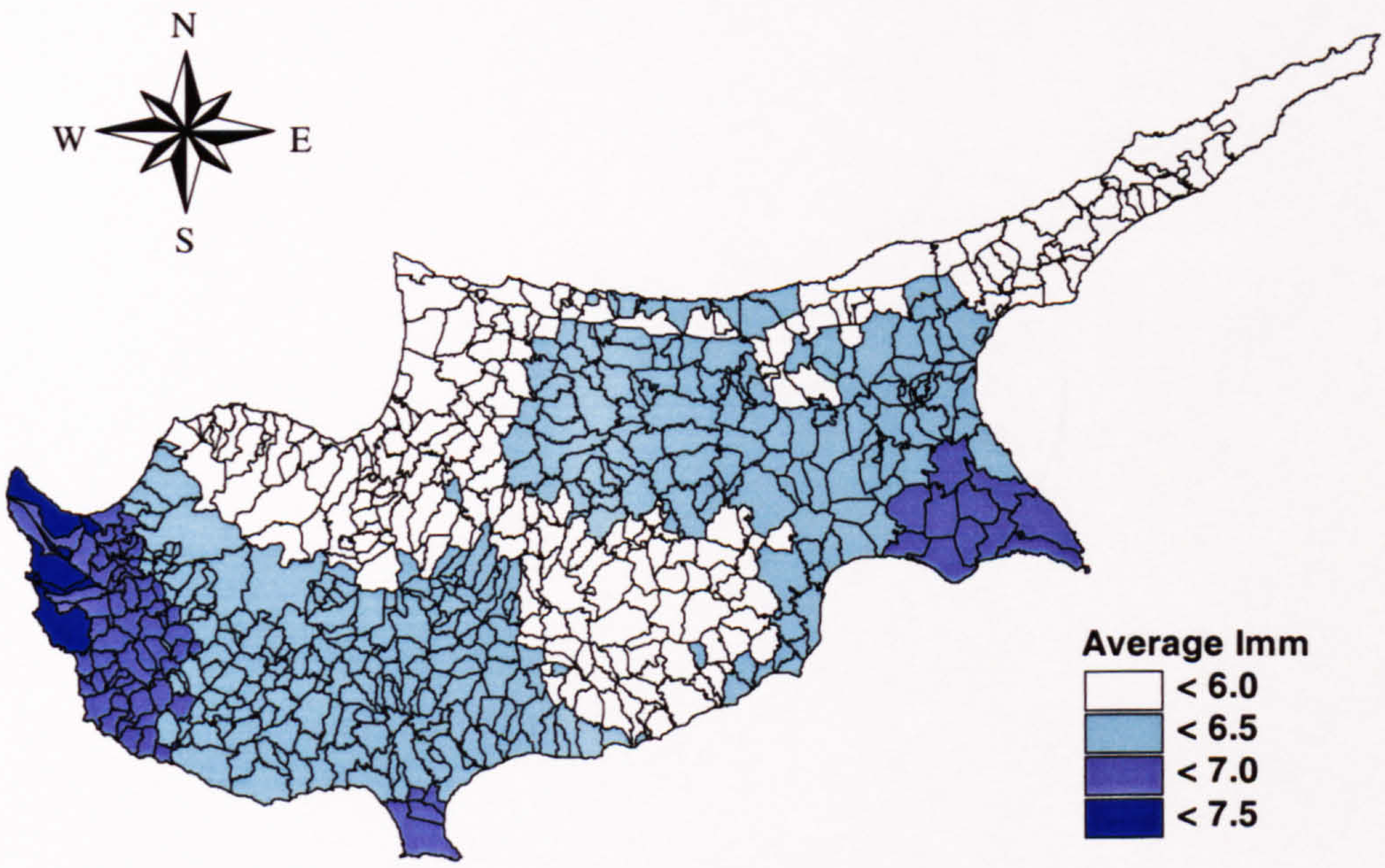


Figure 6.5. Expected maximum intensities in a 103 years

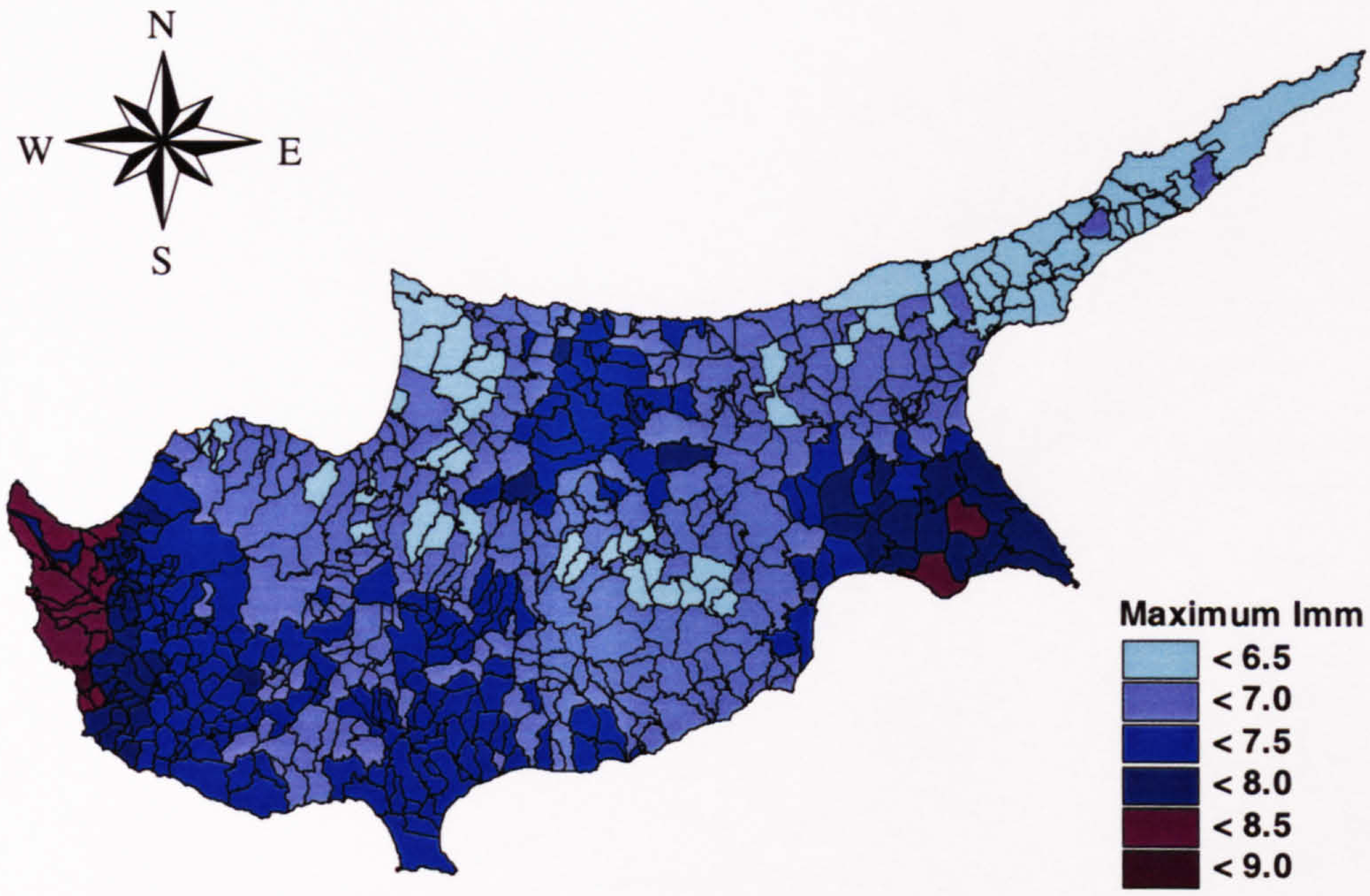


Figure 6.6. Extreme case maximum intensities in a 103 years

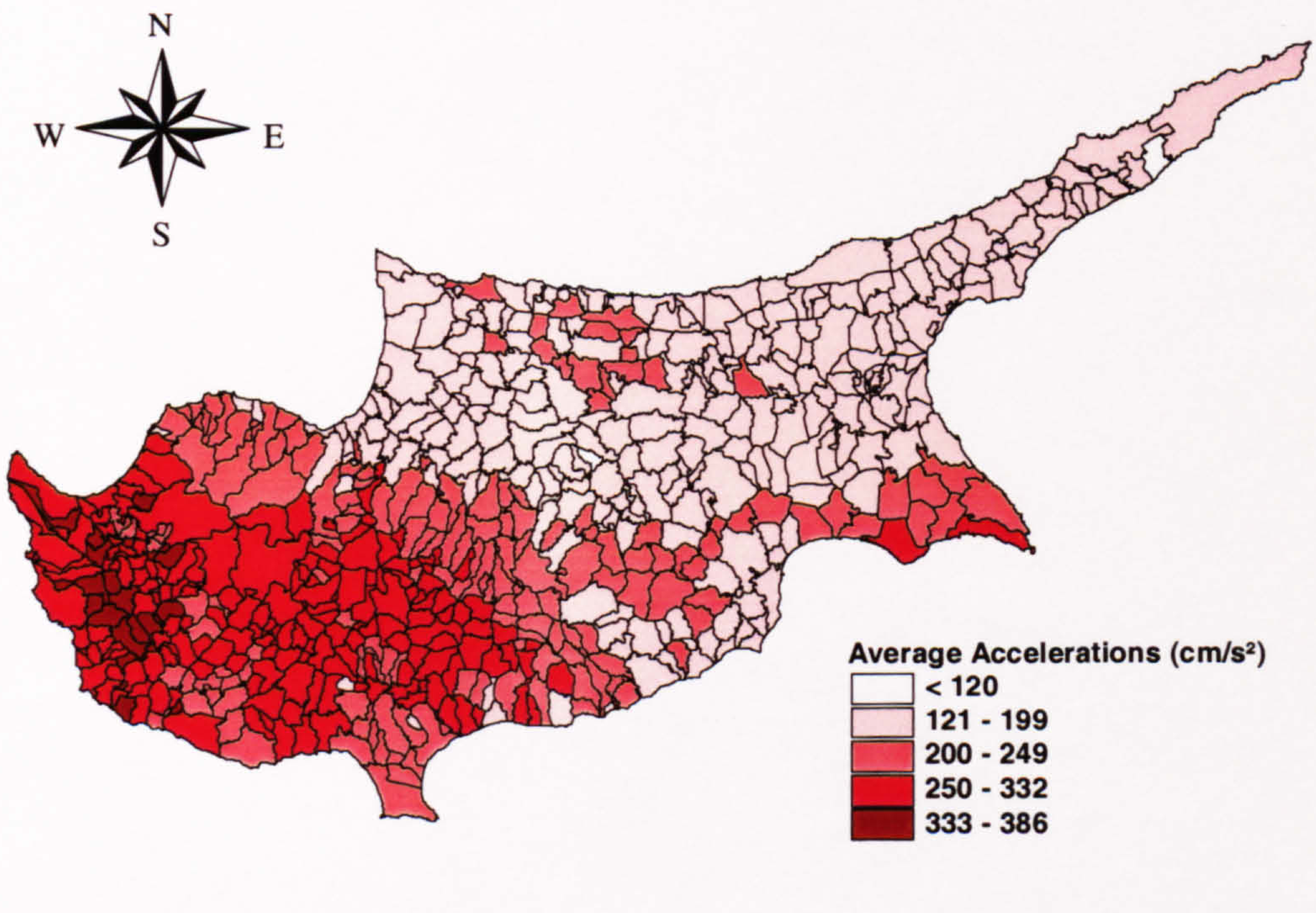


Figure 6.7. Expected maximum accelerations in a 103 years

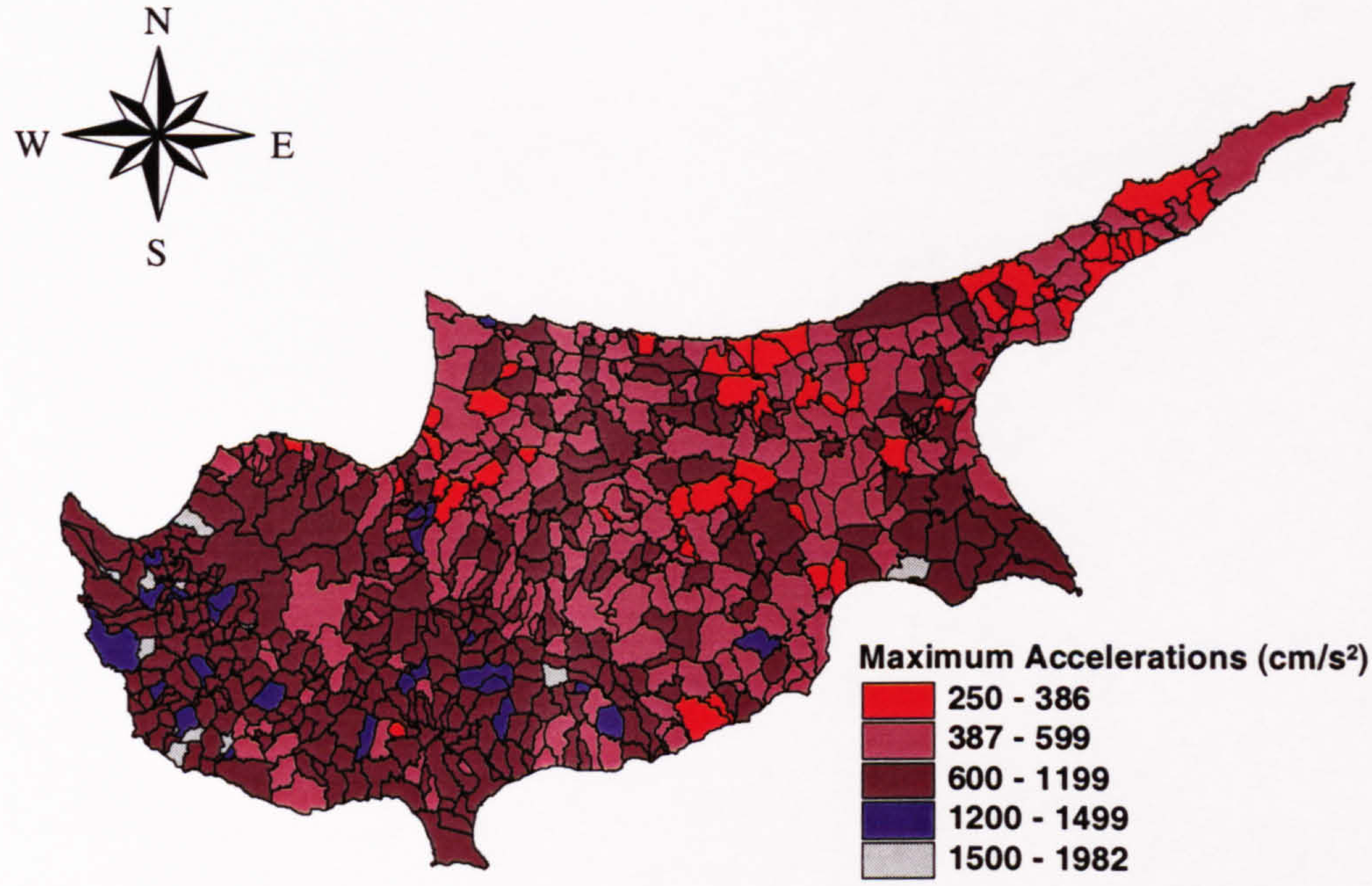


Figure 6.8. Extreme case maximum accelerations in a 103 years

It is clear that Figure 6.6 and Figure 6.7 differ considerably from the seismic hazard map of Cyprus (Figure 2.12) both qualitatively and quantitatively.

The qualitative difference appears to be more a result of the effect of geology. It appears that the hazard maps of Cyprus were devised by allowing a much more dominant effect of the geology, increasing the hazard in the coastal zones and decreasing it on the Troodos mountain.

The main reason they differ quantitatively is because the hazard map is supposed to reflect design values that are usually calculated so that they are not exceeded with a POE-5%.

Since it is very time consuming to estimate the intensities with a POE-5% for all the regions and for different periods of time the four main towns, Nicosia, Larnaca, Limassol and Paphos, were selected and further studies regarding the intensities (Figure 6.9) and accelerations (Figure 6.10) experienced in their municipalities were performed. The POE-50% and POE-5% for the intensities and accelerations of the main cities in the island of Cyprus are shown in Table 6.2 and Table 6.3 respectively.

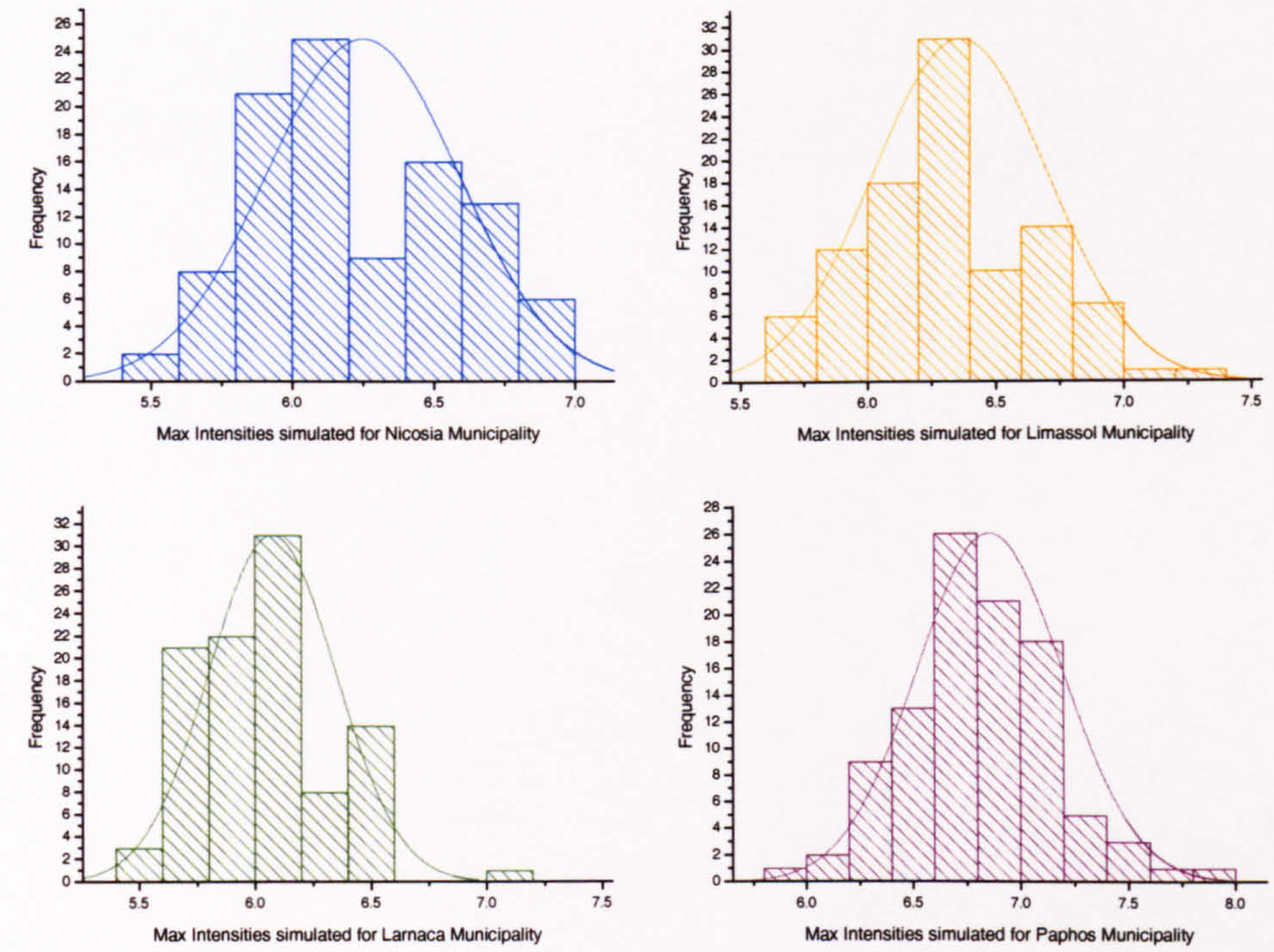


Figure 6.9. Maximum intensities for the municipalities of the main towns for a period of 103 years

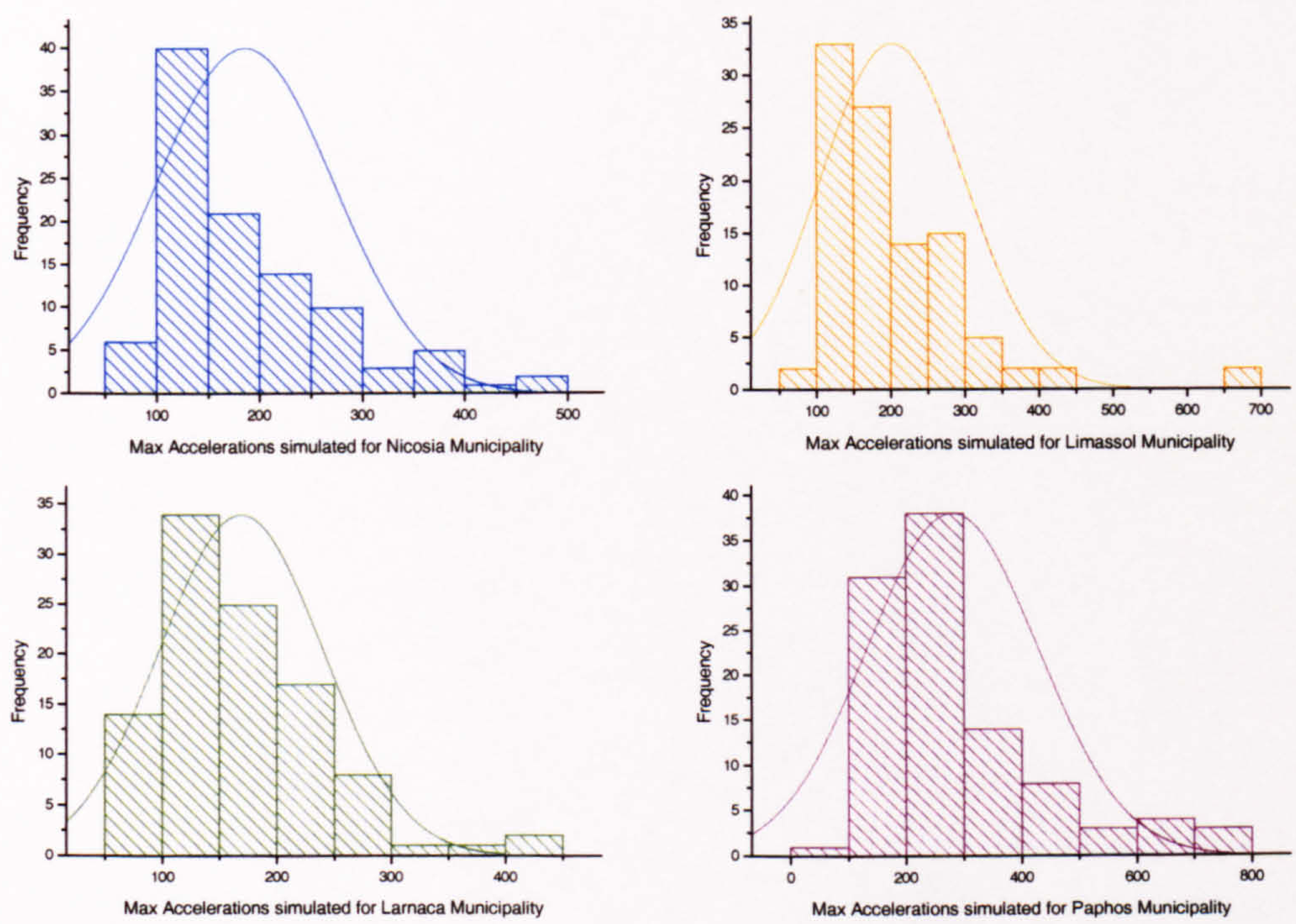


Figure 6.10. Maximum accelerations for the municipalities of the main towns for a period of 103 years

Table 6.2. The POE-50% and POE-5% for the intensities of the main cities in the island of Cyprus for 1, 25, 50 and 100 years

Intensities I_{MM}		Maximum	1 Year	25 Years	50 Years	100 Years
Nicosia	POE-50%	6.20	0.00	5.50	5.80	5.80
	POE-5%	6.90	5.10	6.50	6.70	6.70
	Average	6.25	1.42	5.54	5.73	5.74
Larnaca	POE-50%	6.10	0.00	5.60	5.80	5.80
	POE-5%	6.50	5.30	6.30	6.40	6.40
	Average	6.07	1.31	5.47	5.78	5.81
Limassol	POE-50%	6.30	0.00	5.60	5.80	6.00
	POE-5%	6.90	5.50	6.30	6.40	6.60
	Average	6.36	1.42	5.61	5.84	5.97
Paphos	POE-50%	6.80	0.00	6.10	6.60	6.80
	POE-5%	7.40	5.50	7.10	7.30	7.30
	Average	6.86	1.43	5.93	6.55	6.76

Table 6.3. The POE-50% and POE-5% for the accelerations of the main cities in the island of Cyprus for 1, 25, 50 and 100 years

Accelerations (cm/s^2)		Maximum	1 Year	25 Years	50 Years	100 Years
Nicosia	POE-50%	158.77	0.00	86.71	107.18	120.72
	POE-5%	377.95	60.19	246.05	264.56	282.35
	Average	186.06	11.95	103.30	125.45	137.42
Larnaca	POE-50%	157.09	0.00	78.86	108.78	119.65
	POE-5%	284.17	61.20	213.73	247.35	262.33
	Average	168.94	11.29	94.95	121.80	134.47
Limassol	POE-50%	171.69	0.00	97.68	122.82	138.29
	POE-5%	357.36	77.58	248.19	271.72	299.02
	Average	202.69	14.16	110.80	140.04	160.46
Paphos	POE-50%	229.98	0.00	114.89	169.27	212.79
	POE-5%	640.34	85.03	374.25	454.55	522.35
	Average	280.47	15.97	145.02	203.78	247.95

From the tables it can be seen that the value with POE-5% differs from the mean value considerably, by up to 1 grade of intensity or by100% increase in acceleration.

These studies enabled the derivation of two equations shown in Figure 6.11 and Figure 6.12. These equations allow the determination of the average maximum accelerations and intensities at different time periods. These were used for the production of the complete seismic zone map for both accelerations (Figure 6.13) and intensities (Figure 6.14) for the island for various return periods depending on the design need (i.e. construction of houses usually considers a design life for the building of 25 years therefore a map of 25 years return period would be required).

These results also enabled the derivation of two more equations (Figure 6.11 and Figure 6.12) which will be used in the production of the POE-5% seismic zone map for accelerations for the island for 25 year return period. This will be compared to the guidelines of the aseismic code in section 6.4.

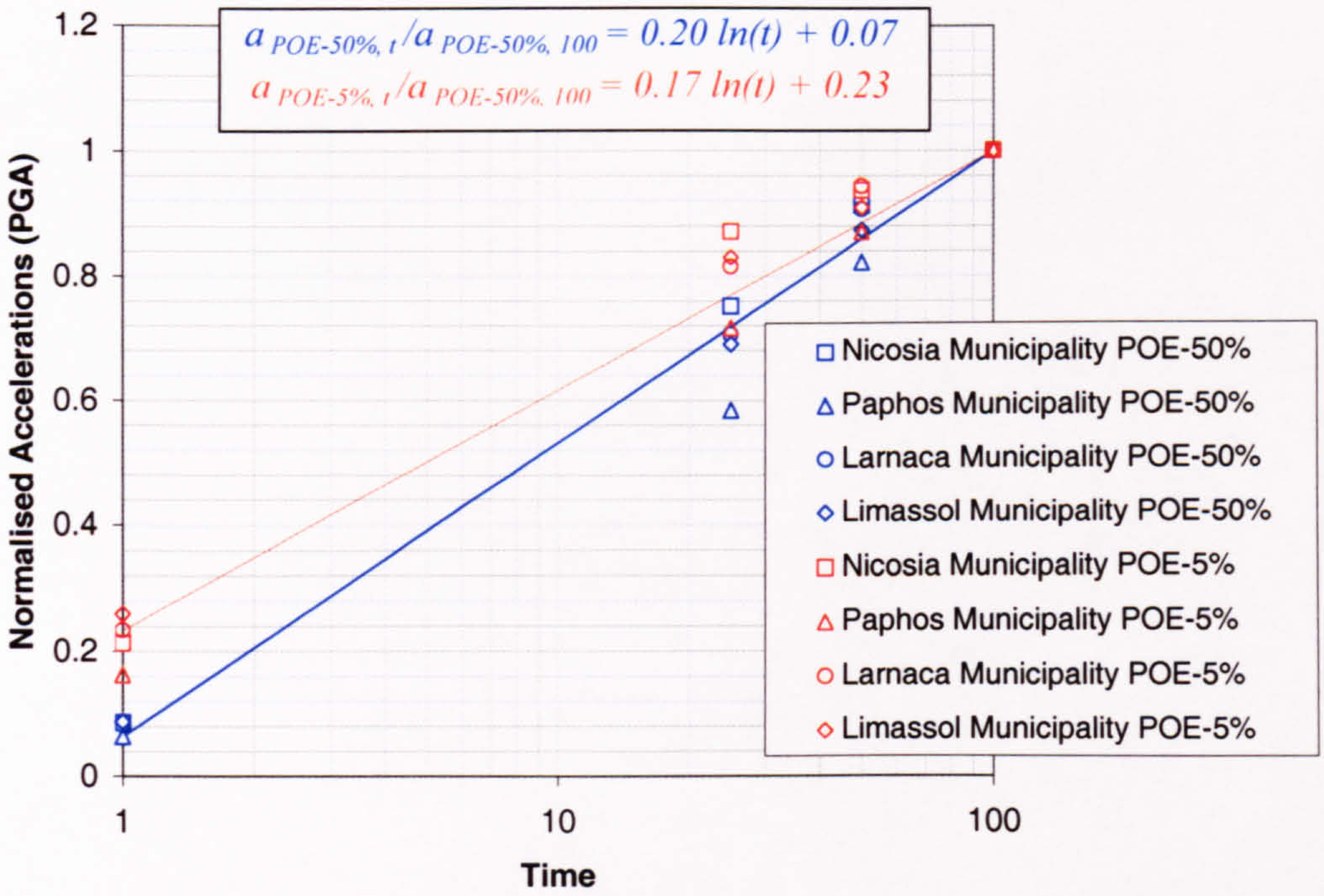


Figure 6.11. POE-50% and POE-5% accelerations in Nicosia, Larnaca, Limassol and Paphos normalised to the 100 years return period

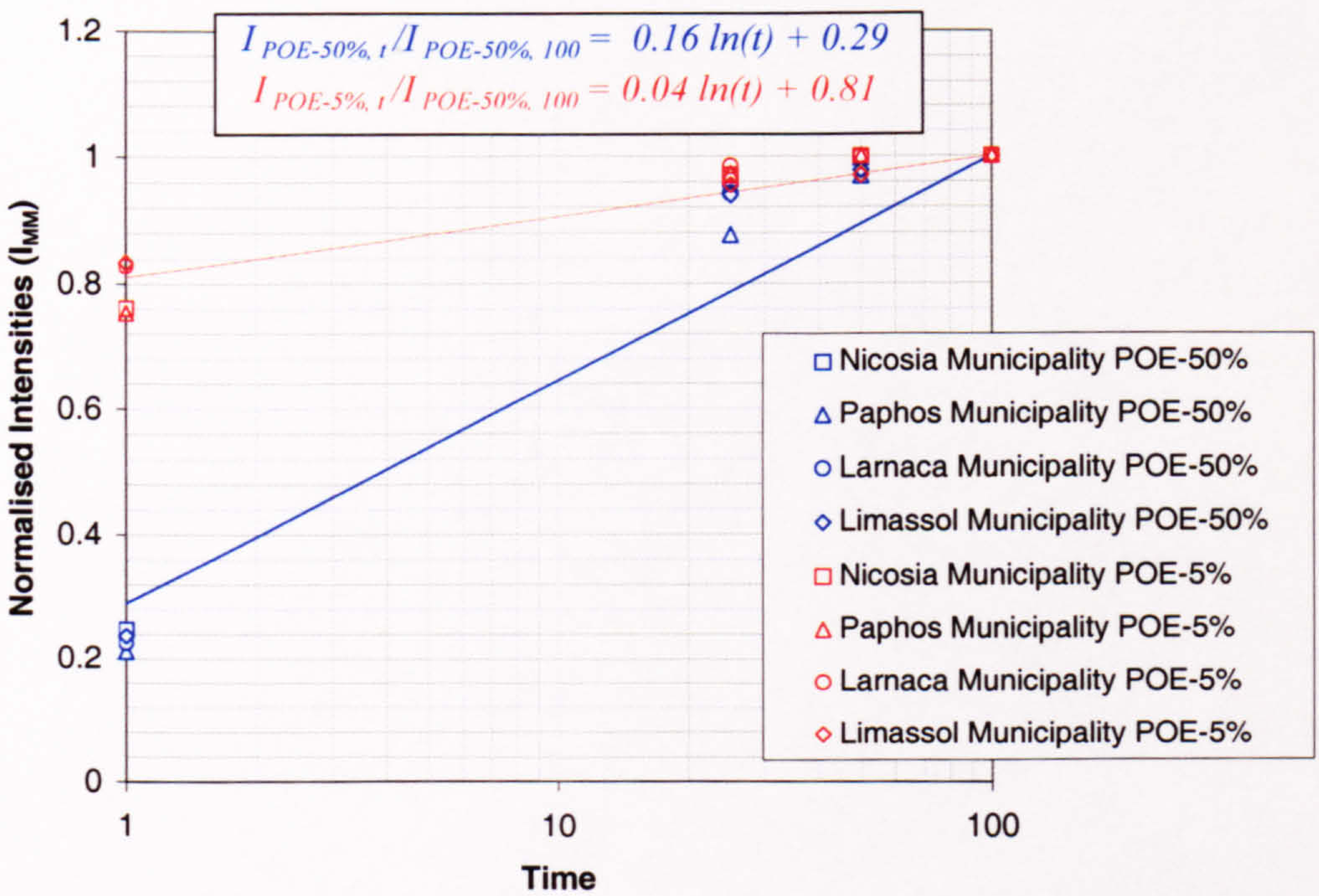


Figure 6.12. POE-50% and POE-5% intensities in Nicosia, Larnaca, Limassol and Paphos normalised to the 100 years return period

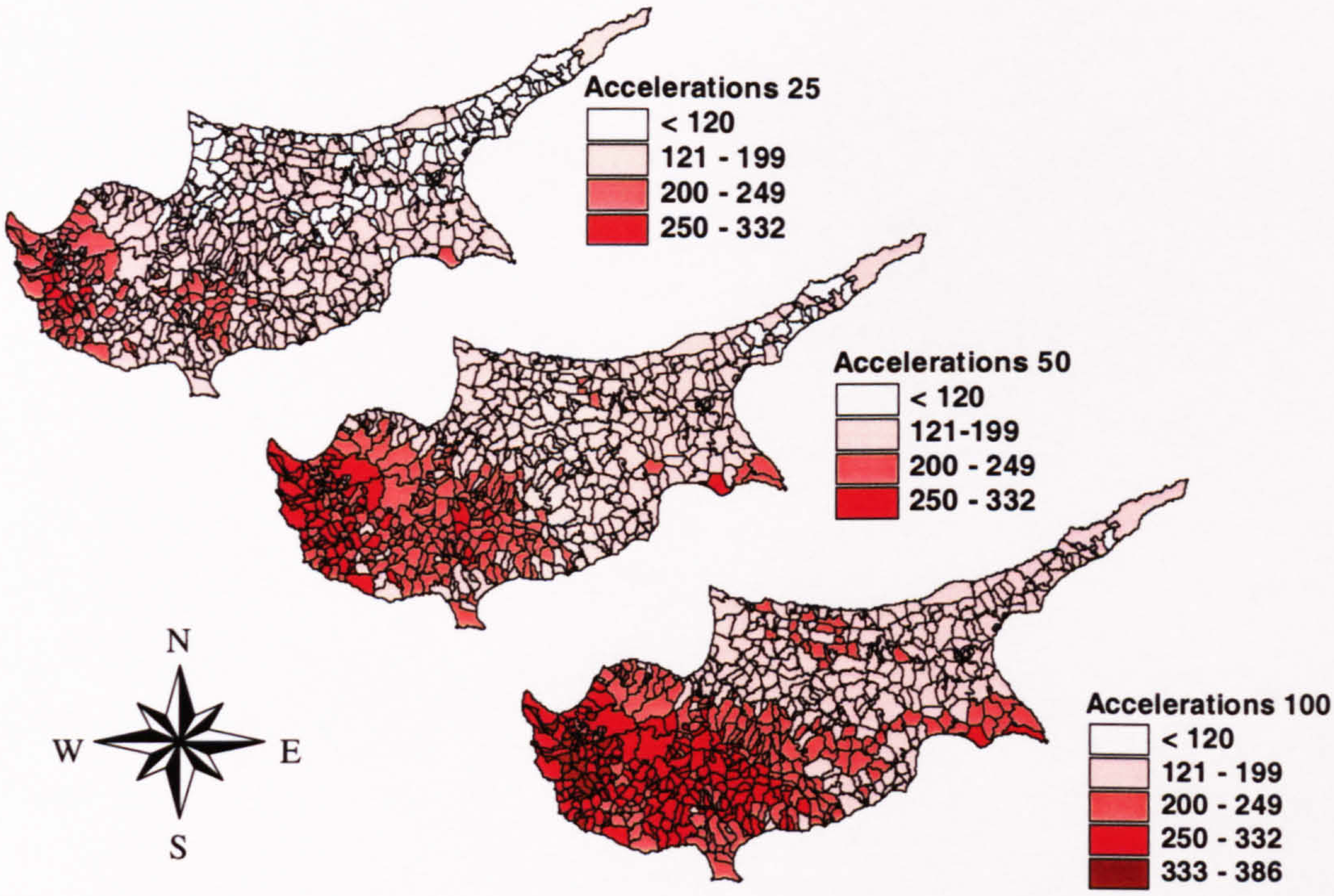


Figure 6.13. **Accelerations (cm/s^2) for a 25, 50 and 100 years return period based on the equation of Figure 6.11**

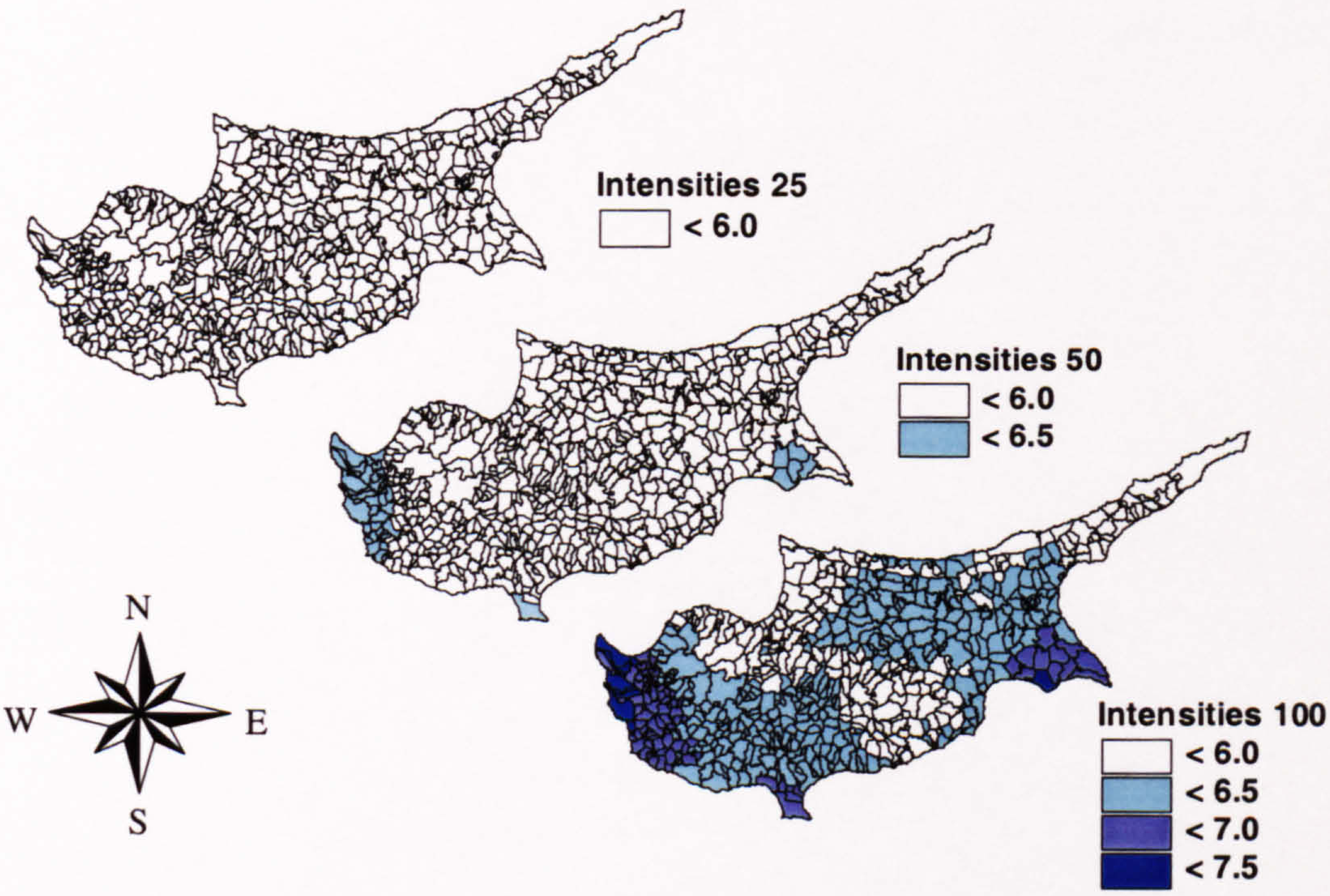


Figure 6.14. **Intensities (I_{MM}) for a 25, 50 and 100 years return period based on the equation of Figure 6.12**

The results presented in section 6.2 give some general information regarding the earthquake risk of Cyprus.

The following section presents two alternative approaches to deal with the hazard uncertainty.

6.3 ASSESSMENT OF THE HAZARD VARIABILITY

6.3.1 INTRODUCTION

The hazard determination and uncertainty is the main problem of ERA. The previous section considered that previous earthquakes would occur again in the same locations. Clearly, that is not likely and hence, the more general probabilistic determination of hazard needs to be examined.

The following section deals with ERA studies involving the Ambraseys (1992) recurrence relationship, as well as the recurrence relationship derived by the author for the whole area in combination with the seismic energy release parameter.

6.3.2 AMBRASEYS RECURRENCE RELATIONSHIP

The Ambraseys (1992) recurrence relationship (equation 2.4) is examined to determine its suitability for the estimation of the earthquake risk.

Random earthquake magnitudes were generated based on the recurrence relationship derived by Ambraseys (1992) for the relevant geographic area 33.0°-37.0° N and 31.0°-35.5°E. The co-ordinates of the events were generated randomly (shown in Figure 6.15) based on the assumption of uniform spatial distribution implicit in the equation. The total number of events in each simulation series was determined as follows: Only events with $M_S>4.5$ were selected (events likely to cause damage). Once an earthquake with $M_S\geq7$ was obtained the generation of events stops. According to the equation of Ambraseys (equation 2.4) such an event has a return period of 95 years which is the period chosen for the simulations.

Further event characteristics such as the time of occurrence (i.e. year, month and time of day) were also randomly generated based on a uniform probability over the period examined. That is, a random number between 1-95 was selected to determine the year, 1-12 for the month and 1-24 for the time of the day for each earthquake.

As far as the depths of the events are concerned, though the equation does not try to predict that, they were assumed to be shallow. This decision was based on the conclusions made during the study involving the earthquake depths, which showed that the events, which caused significant damage to the island were generally shallow. However, future work could involve a study of the relation between the M_S and the depth of the events so that a better representation of this parameter can be achieved.

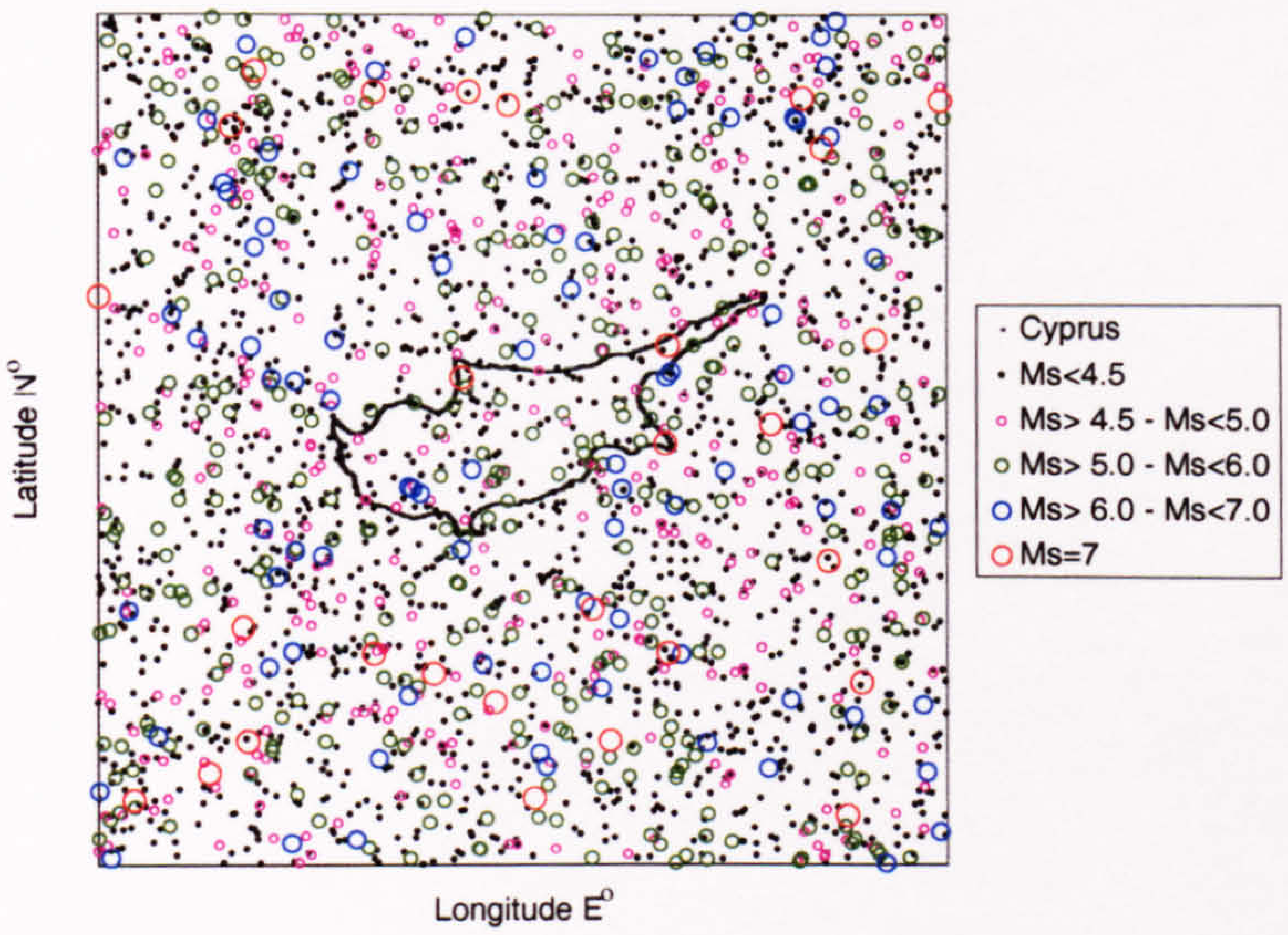


Figure 6.15. The spatial distribution of the randomly generated M_S for the simulated catalogues

A study to examine whether the new randomly generated earthquake catalogues follow the Ambraseys recurrence relationship was performed, and the results shown in Figure 6.16 are quite satisfactory.

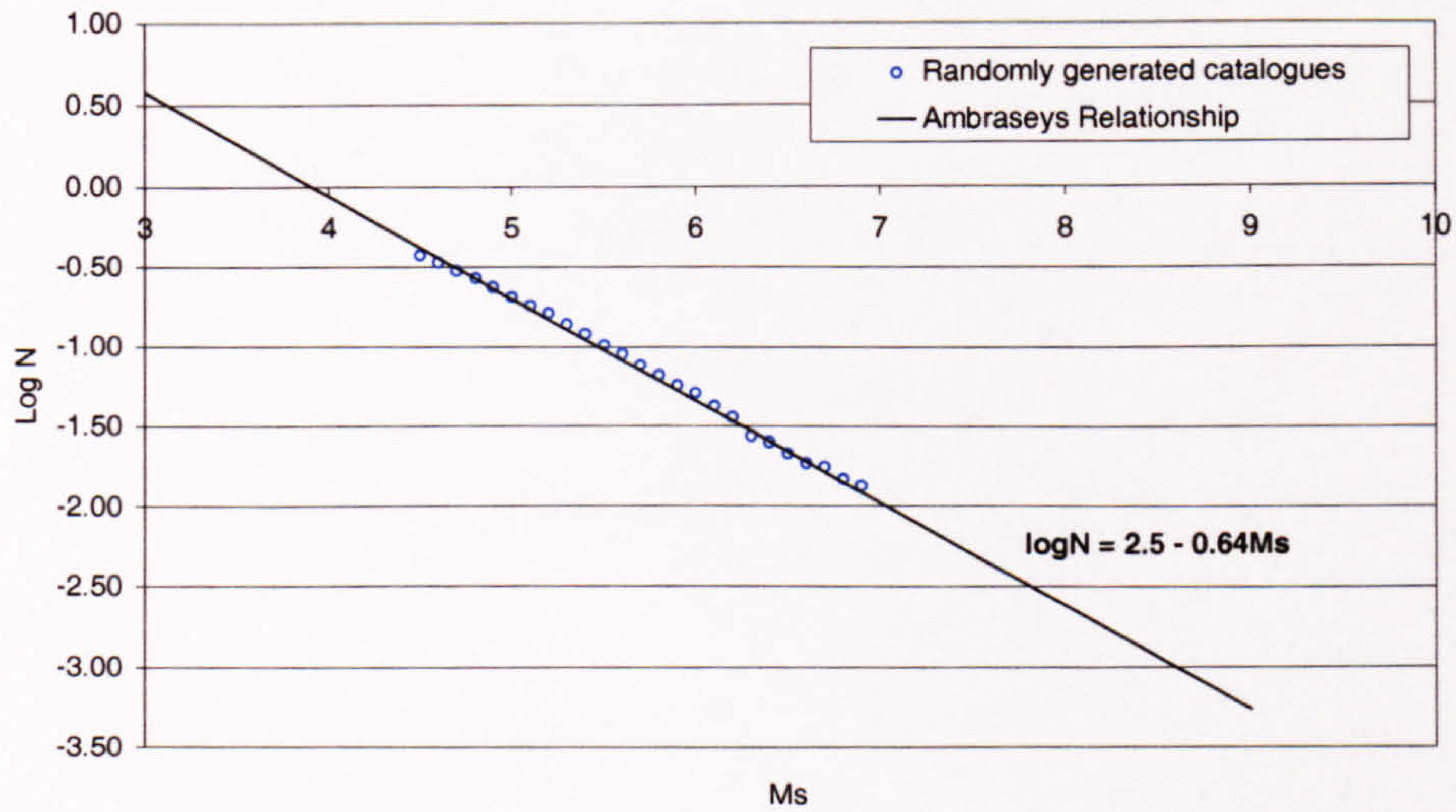


Figure 6.16. Comparison of Ambraseys recurrence relationship with the randomly generated M_S

Twenty-four series of earthquakes were determined. This number of simulations is not thought to be enough to arrive at definite conclusions, but due to time restriction it was decided that they would be sufficient to indicate the trend of the results.

The simulated catalogues, each representing the events likely to occur within a 95 year period, where analysed through the EQ-RACY model and the expected total earthquake risk, damages, fatalities and injuries were estimated (Figure 6.17).

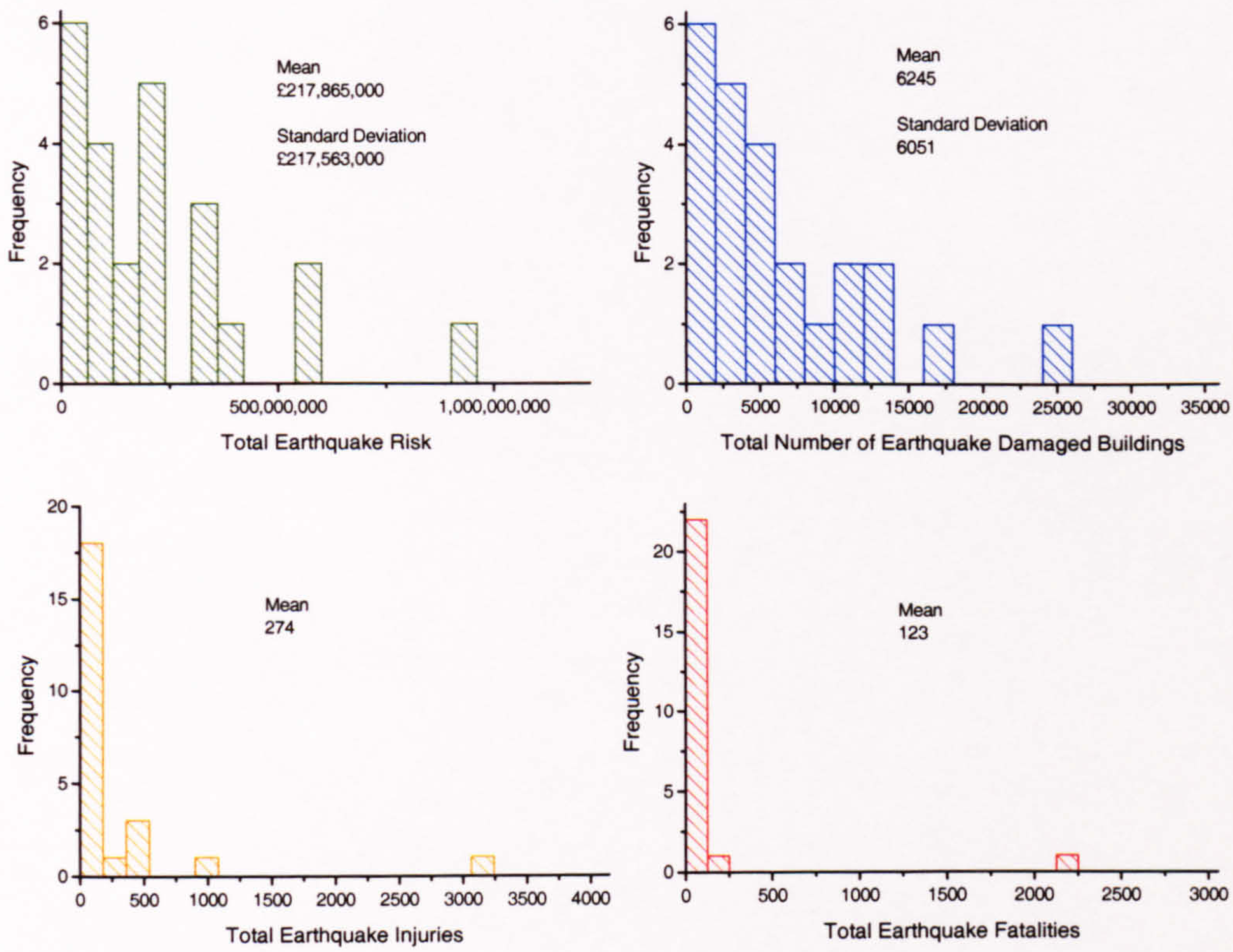


Figure 6.17. Total earthquake risk, damages, fatalities and injuries for a period of 95 years

It is clear that the distributions differ from the ones of the previous study, and the mean values are much lower than calculated previously.

In addition to the total risk, average annual values (Figure 6.18) and average annual values per building (Figure 6.20) were estimated. The earthquake risk for a 10, 25 and 50 year periods were also calculated (Figure 6.20). Further studies involving the intensities and accelerations were also performed and are presented in Figure 6.21 and Figure 6.22.

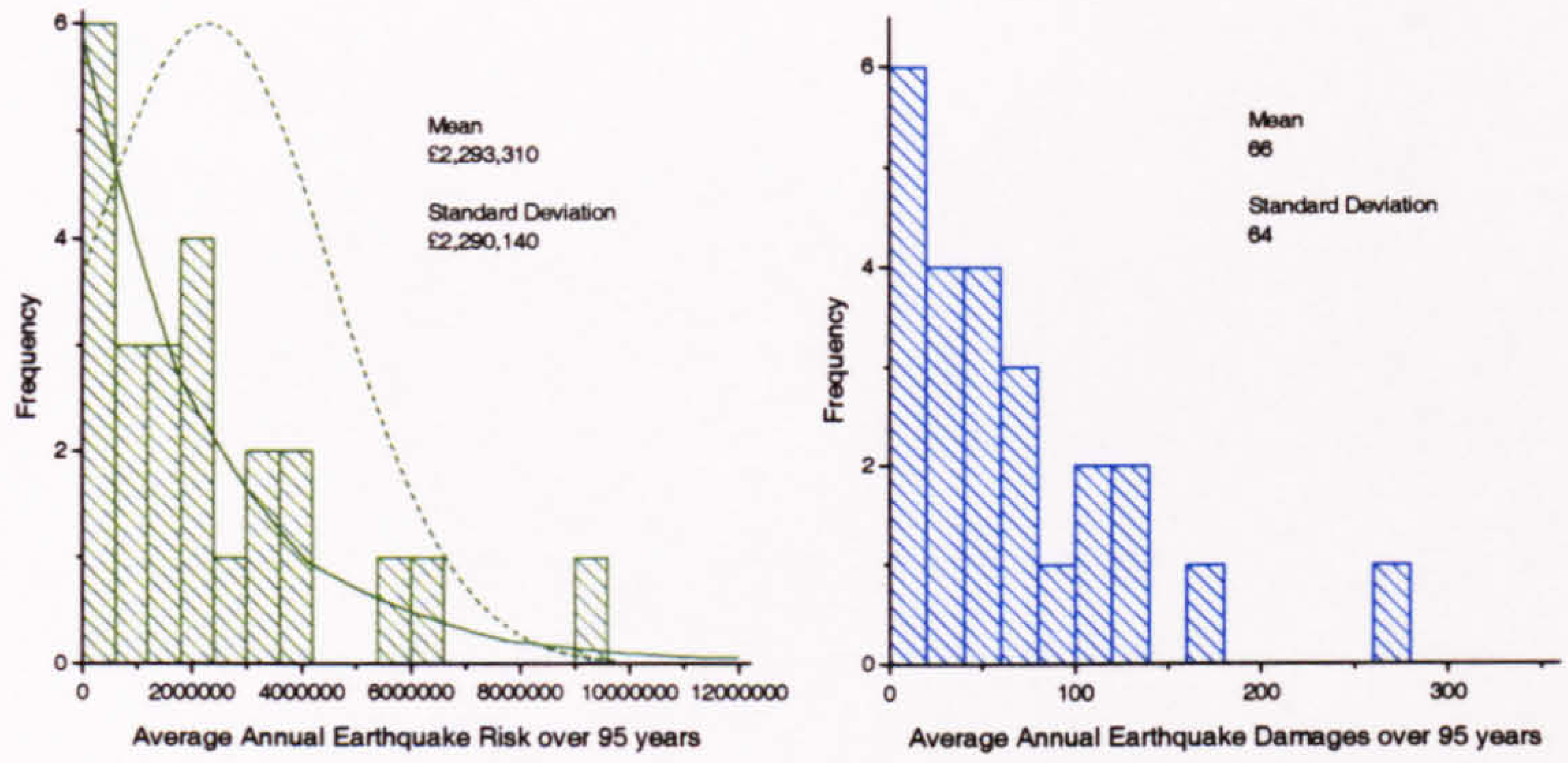


Figure 6.18. Average annual earthquake risk, damages, fatalities and injuries over 95 years

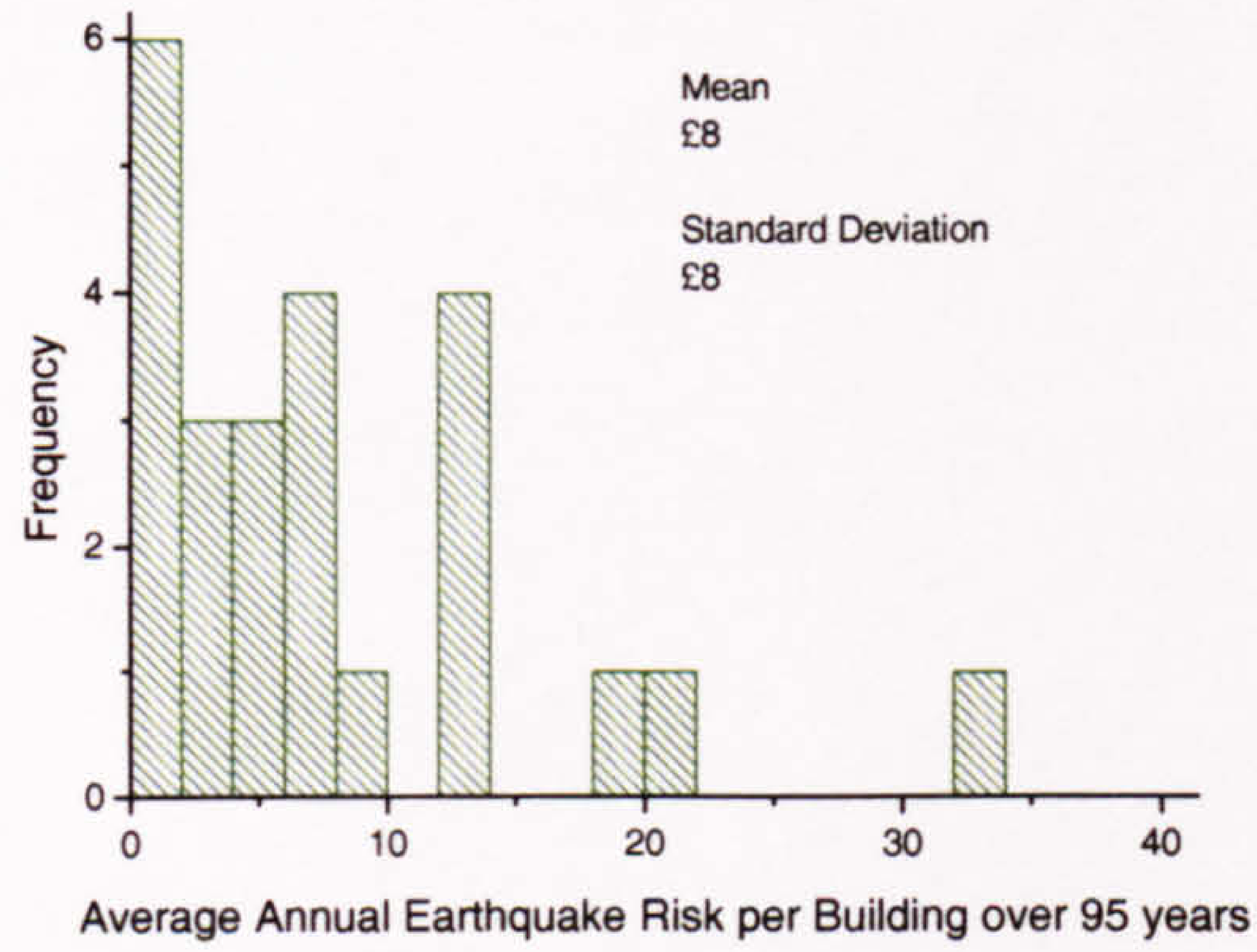


Figure 6.19. Average annual earthquake risk per building over a 95 year period

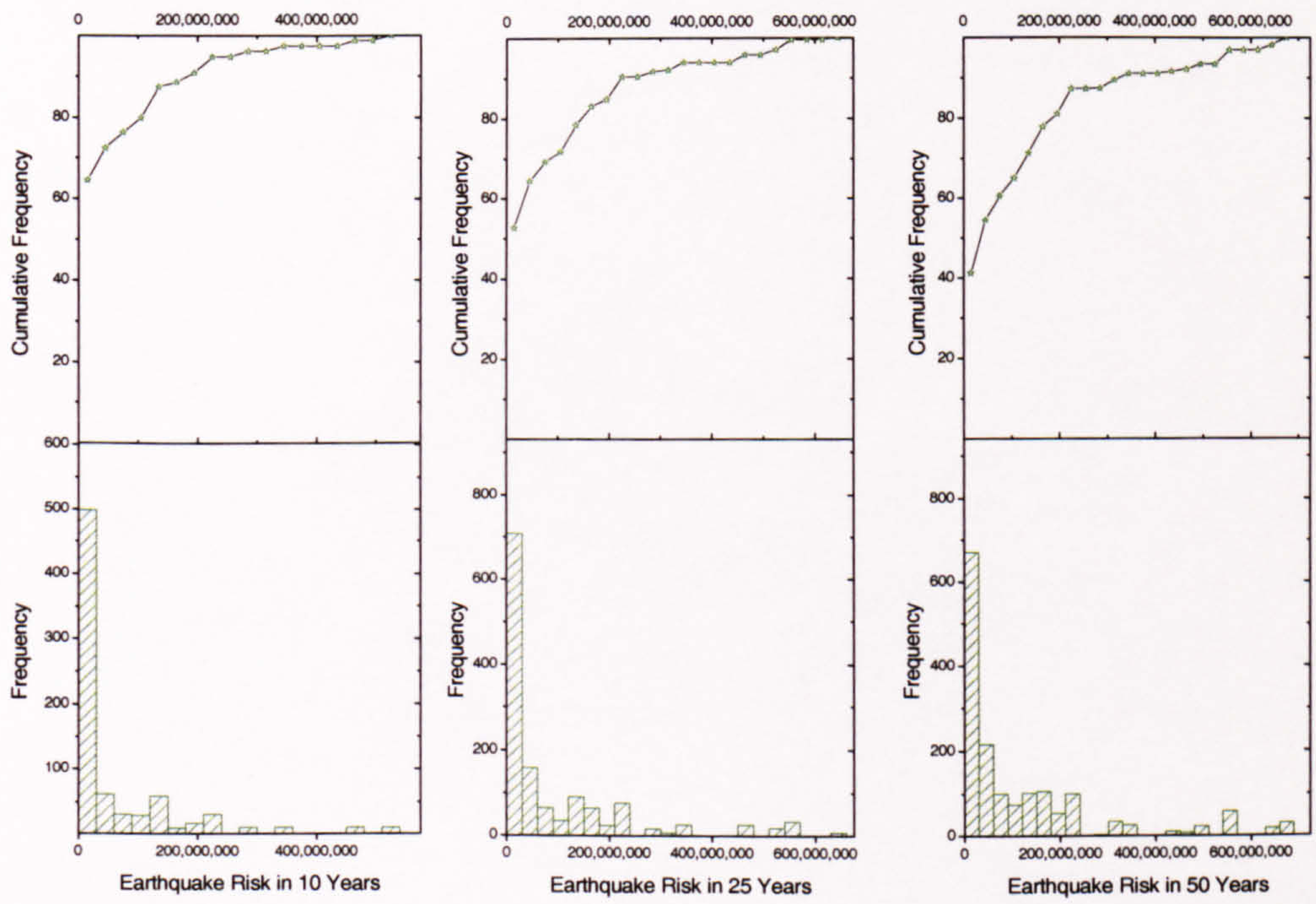


Figure 6.20. The earthquake risk for a period of 10 years, 25 years and 50 years

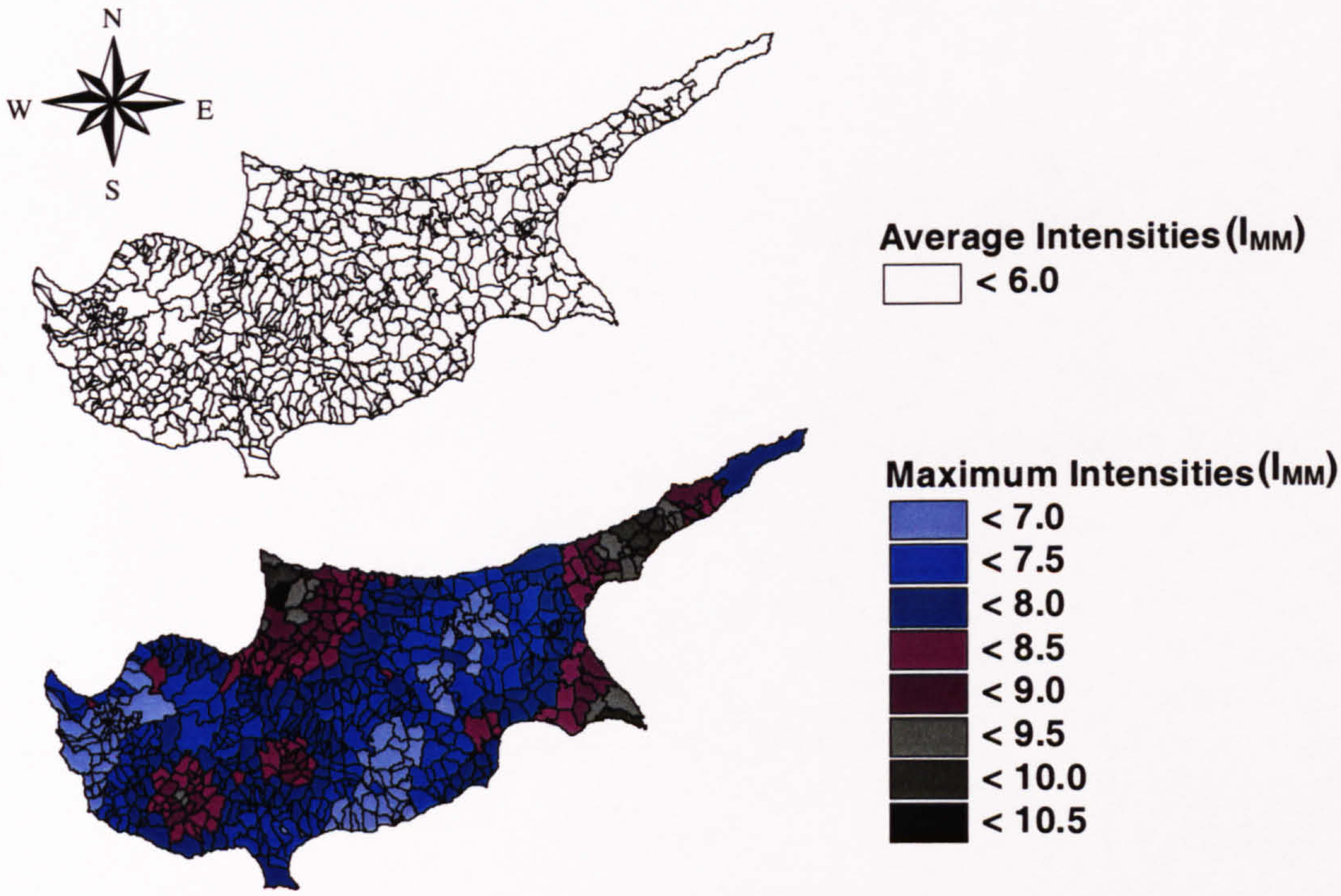


Figure 6.21. Expected maximum intensities and extreme case maximum intensities in 95 years

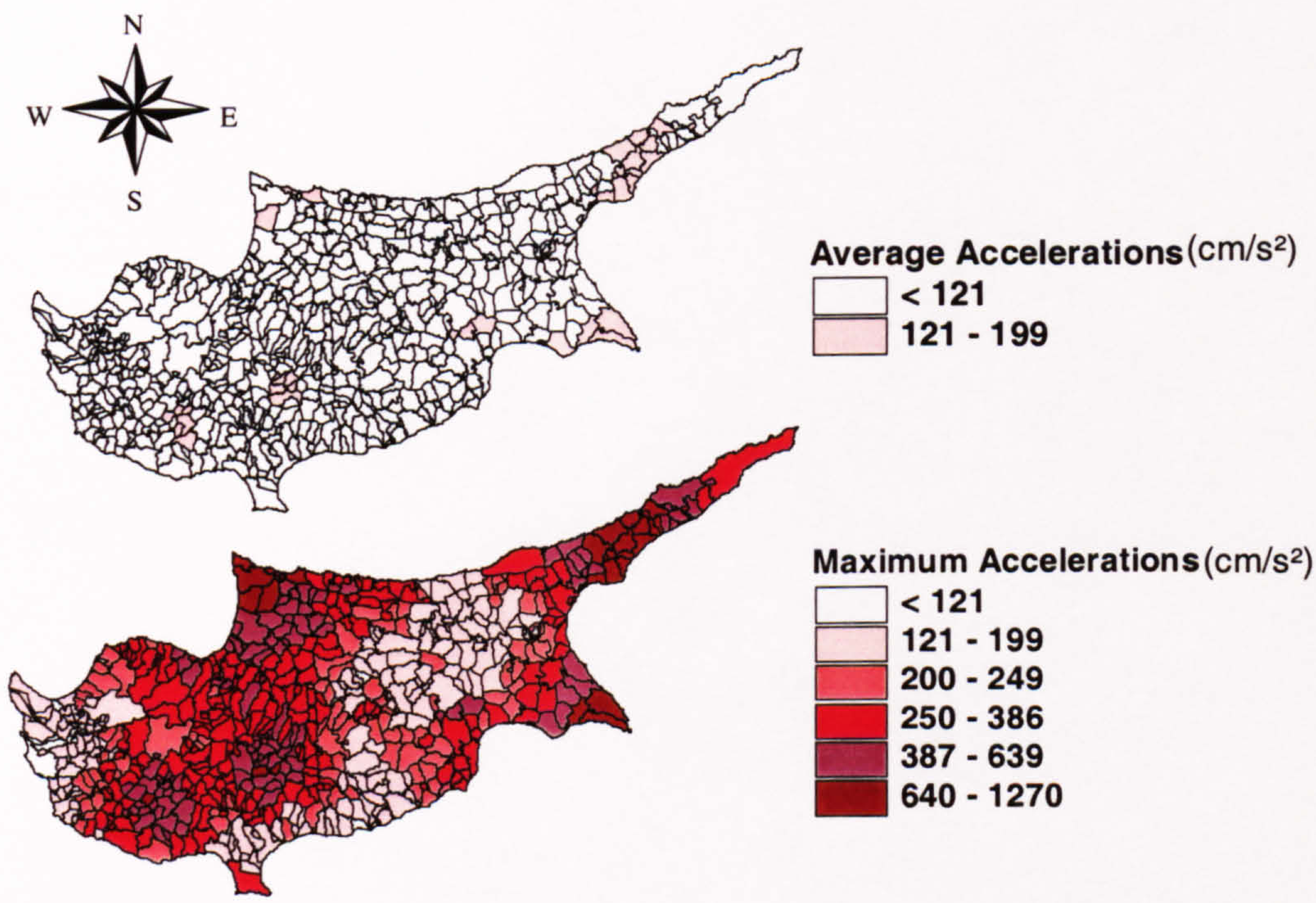


Figure 6.22. Expected maximum accelerations and extreme case maximum accelerations in 95 years

The results do not comply with the earthquake risk, damages, fatalities and injuries estimated based on the historic catalogue of the island and the values obtained are much lower. Direct comparisons are not undertaken since more simulations would be necessary to make them meaningful.

The assumption of a uniform spatial distribution for the earthquake events resulted in the simulated catalogues displaying a rather global and more smeared spatial presentation of the events, significantly different from how they are expected to occur.

It can be concluded that this type of equation cannot be used directly for ERA.

6.3.3 WHOLE AREA RECURRENCE RELATIONSHIP AND ENERGY

This study examines the recurrence relationship (Equation 3.3) derived by the author for the geographic area 33.0°-37.0° N and 31.0°-35.5°E based on the complete earthquake catalogue of Cyprus from 1894 to 1997. The recurrence relationship is used in conjunction to the estimated seismic energy released within a 95 year period, based on the same earthquake catalogue.

As with the study for the Ambraseys equation the magnitudes are generated randomly based on just the recurrence relationship, however, in this case their corresponding seismic energy is calculated and added up until the value of the seismic energy release for a 95 year period is reached. The remaining events are discarded. This approach aims to achieve a better representation of a realistic seismic energy release, which in turn will enable a better estimation of the possible earthquake damages.

Once more a uniform spatial distribution (Figure 6.23) is assumed and a random selection for the other relative parameters (i.e. year, month and time of day) was decided. As before the events are assumed to be of shallow depths.

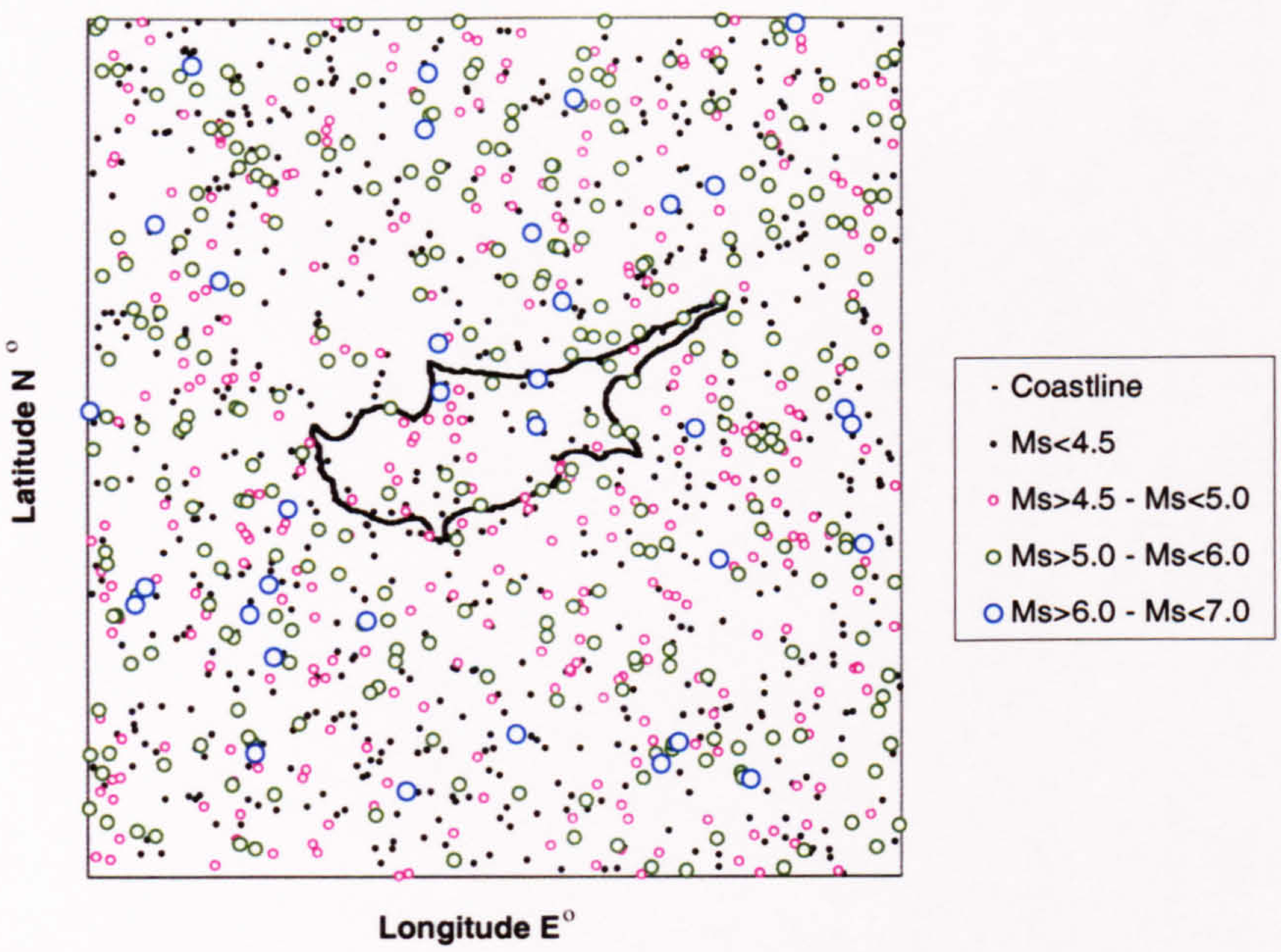


Figure 6.23. The spatial distribution of the randomly generated M_S for the simulated catalogues

The new randomly generated earthquake catalogues were again checked for compliance with the initial equation as shown in Figure 6.24.

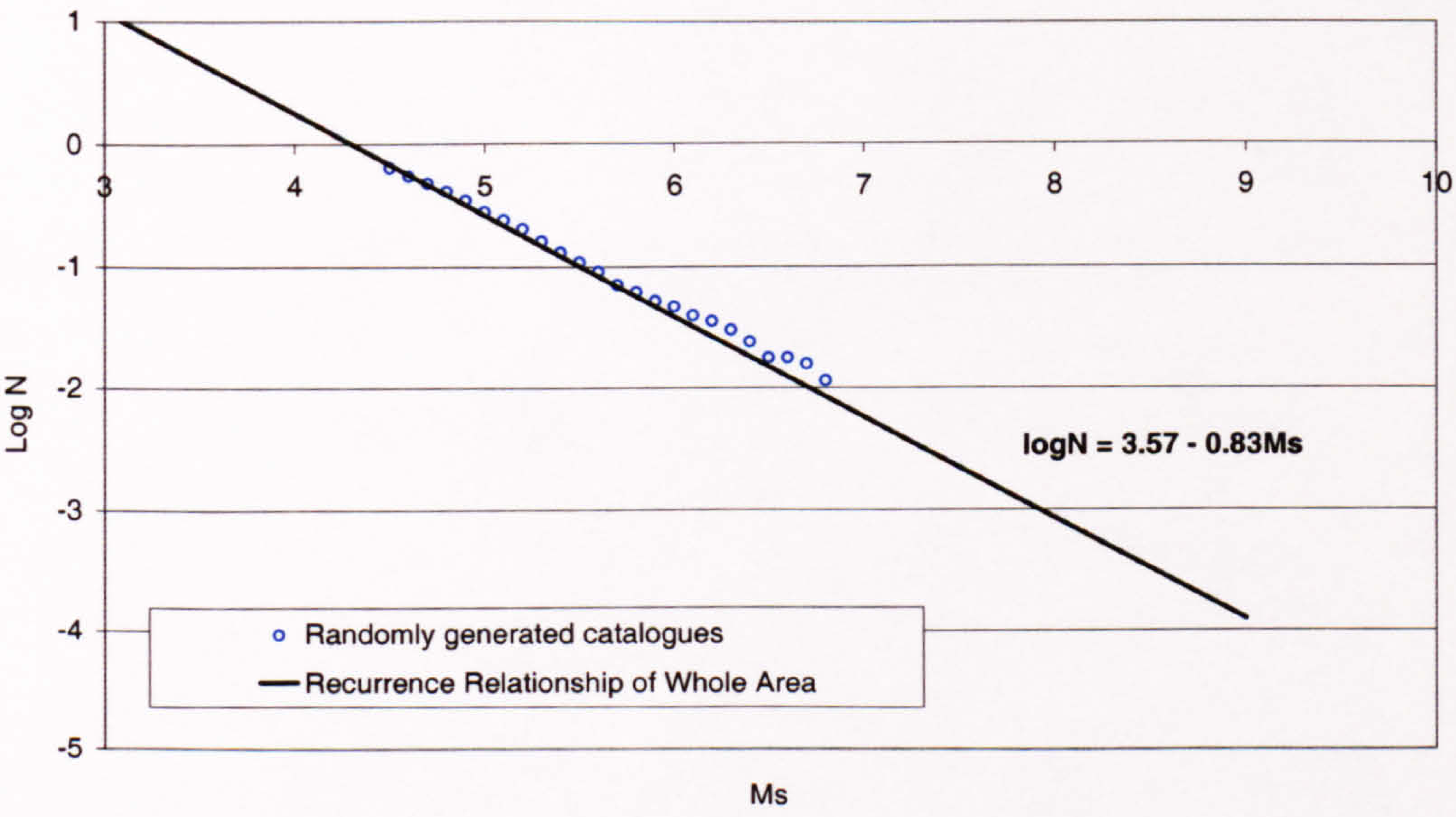


Figure 6.24. Comparison of the recurrence relationship for the whole area with the randomly generated M_S

Twelve catalogues were compiled due to time limitations. The simulated catalogues, each representing the events likely to occur within a 95 year period, where analysed through the EQ-RACY Model and the expected total earthquake risk, damages, fatalities and injuries were estimated (Figure 6.25).

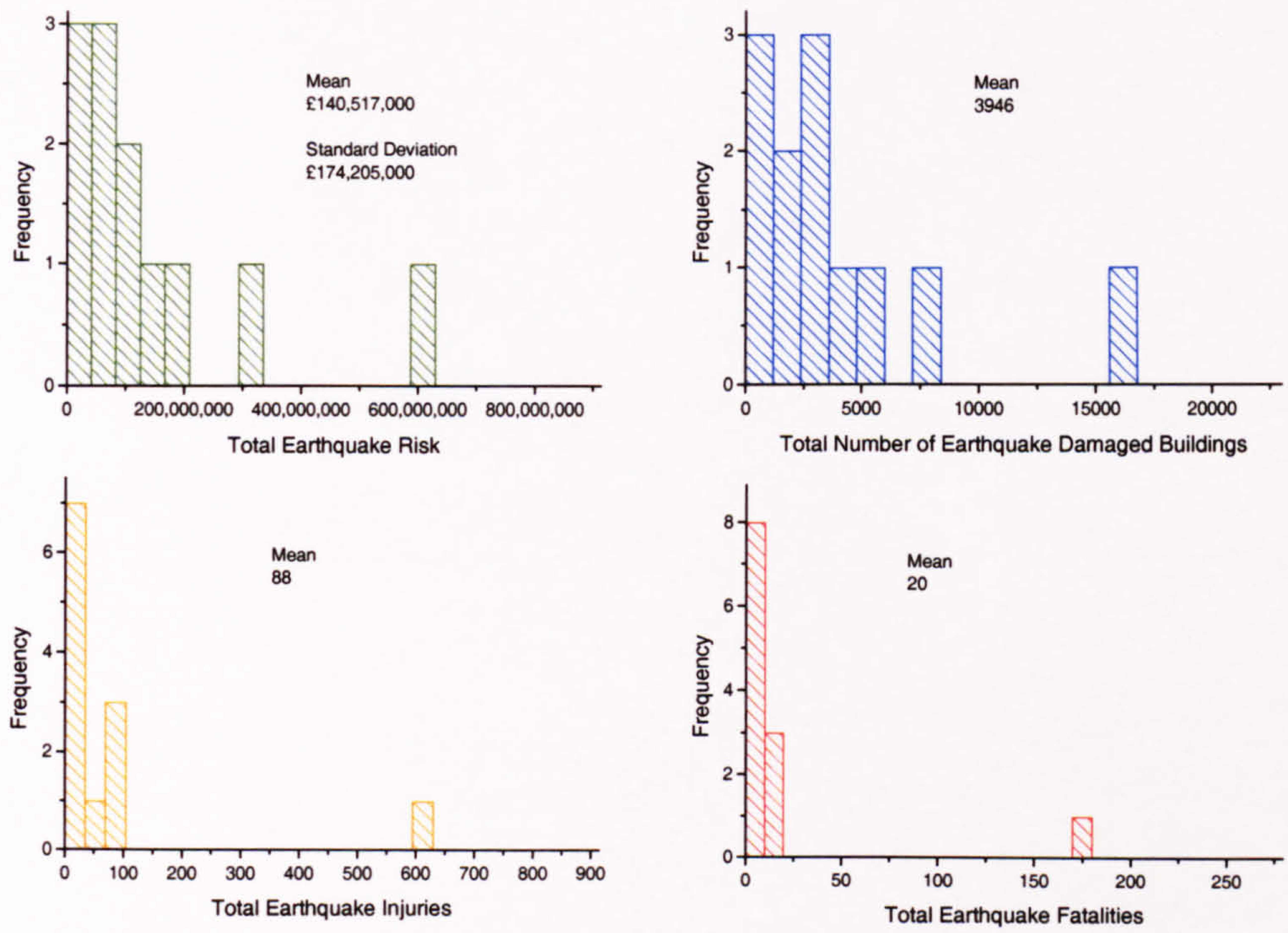


Figure 6.25. Total earthquake risk, damages, fatalities and injuries for a period of a 95 years

In addition to the total earthquake risk, damages, fatalities and injuries their respective average annual values (Figure 6.26) and average annual values per building (Figure 6.27) were estimated. The earthquake risk for a 10, 25 and 50 year periods were also calculated (Figure 6.28). Further studies involving the intensities and accelerations were also performed and are presented in Figure 6.29 and Figure 6.30.

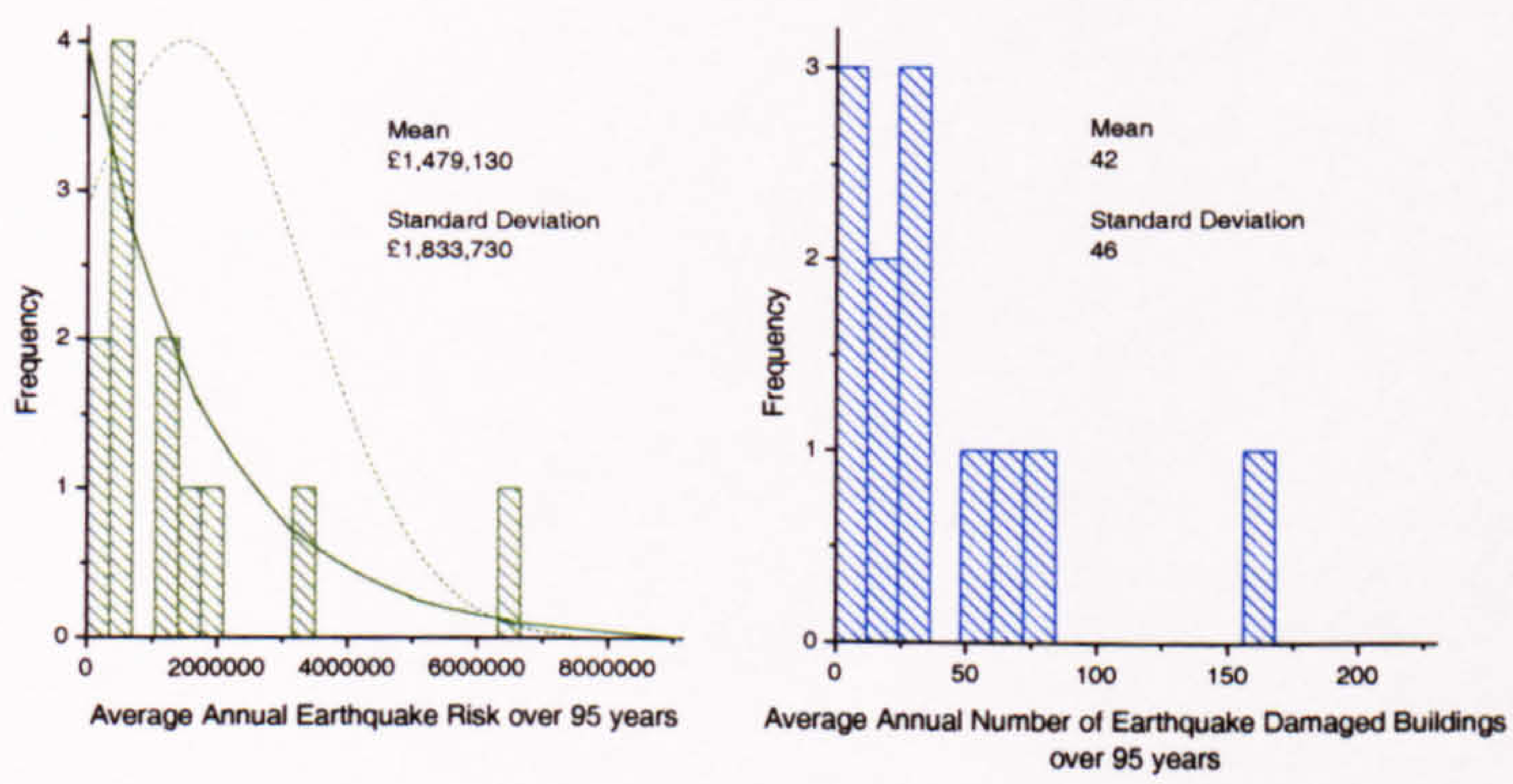


Figure 6.26. Average annual earthquake risk, damages, fatalities and injuries over a 95 year period

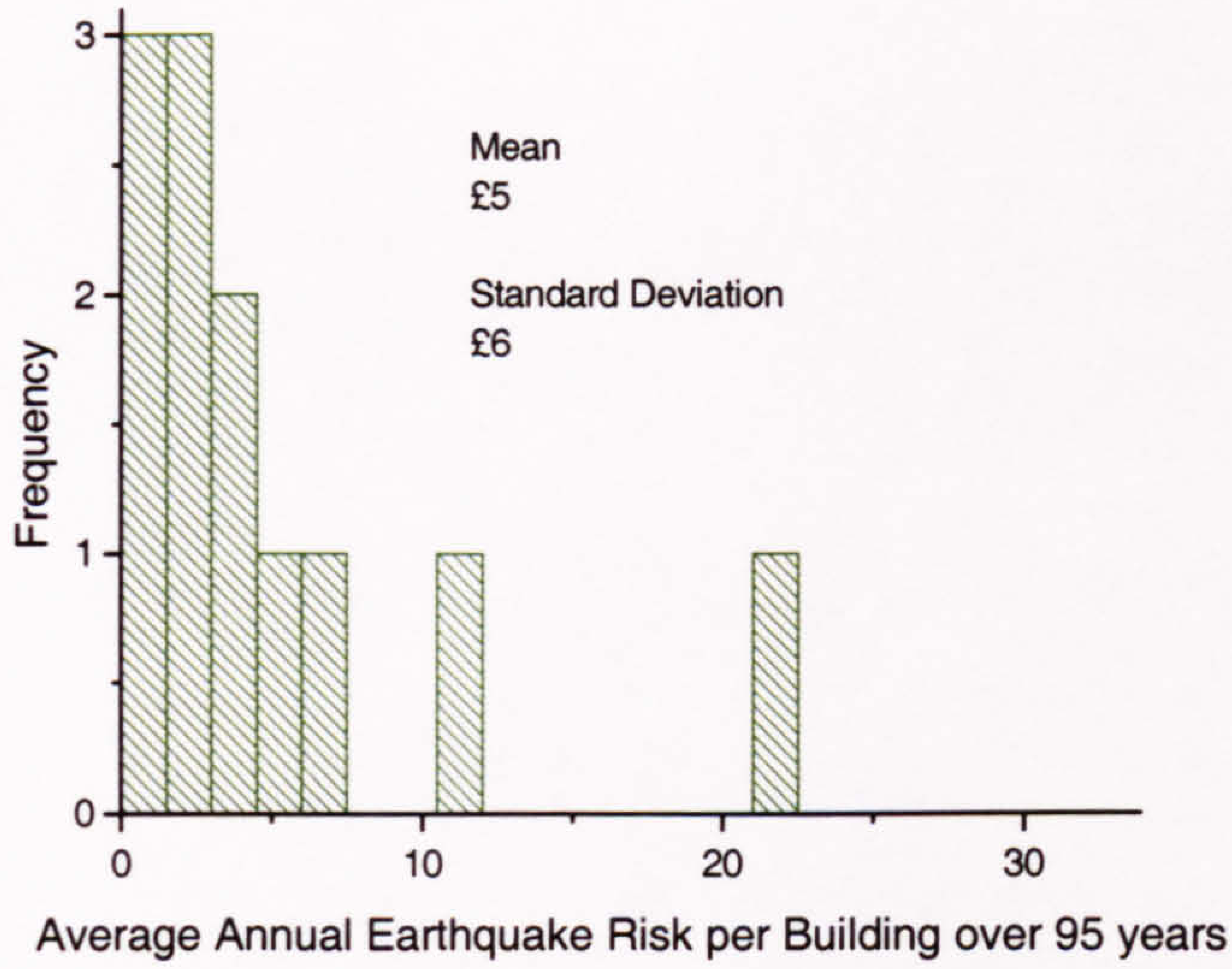


Figure 6.27. Average annual earthquake risk, damages, fatalities and injuries per building over a 95 year period

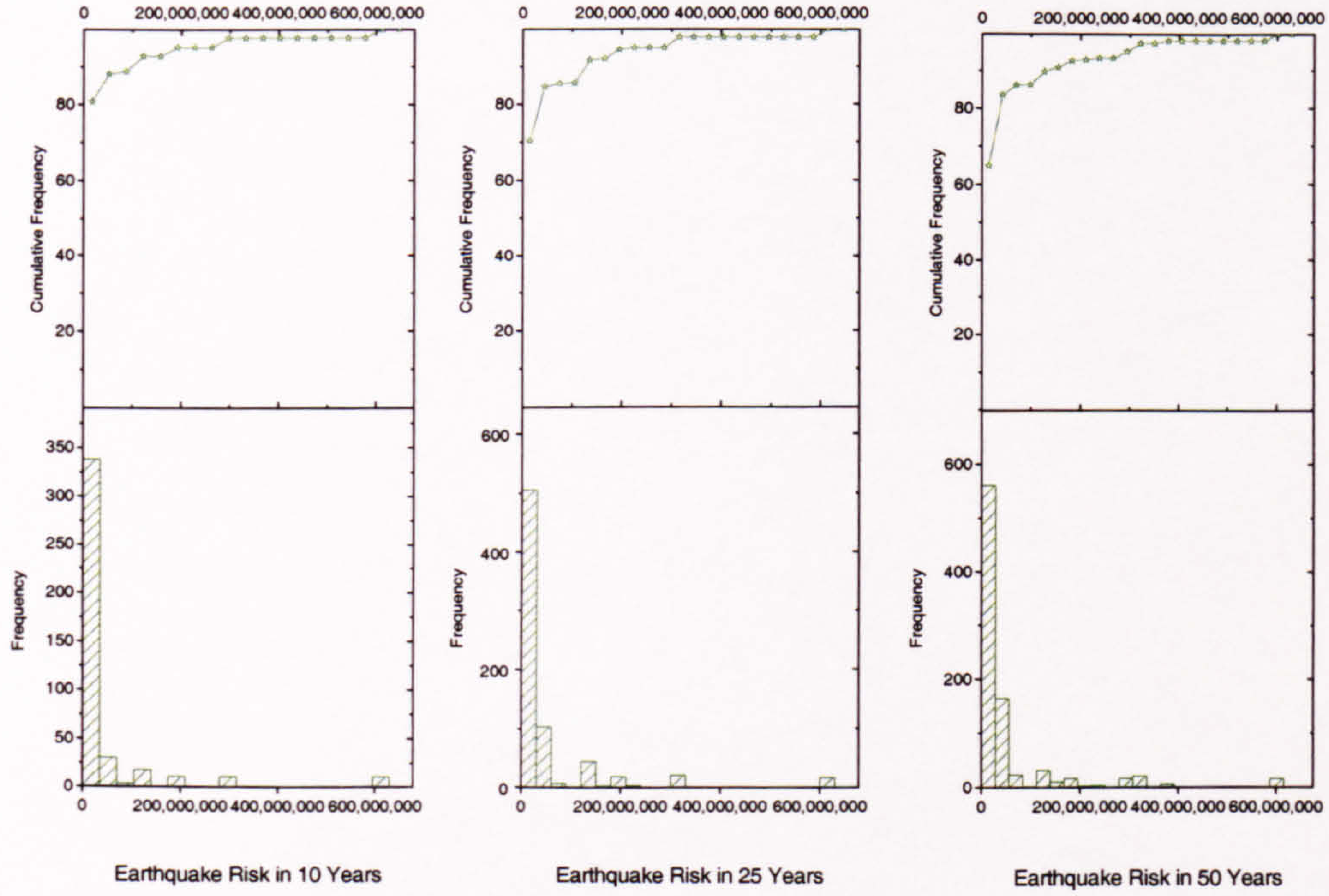


Figure 6.28. The earthquake risk for a period of 10 years, 25 years and 50 years

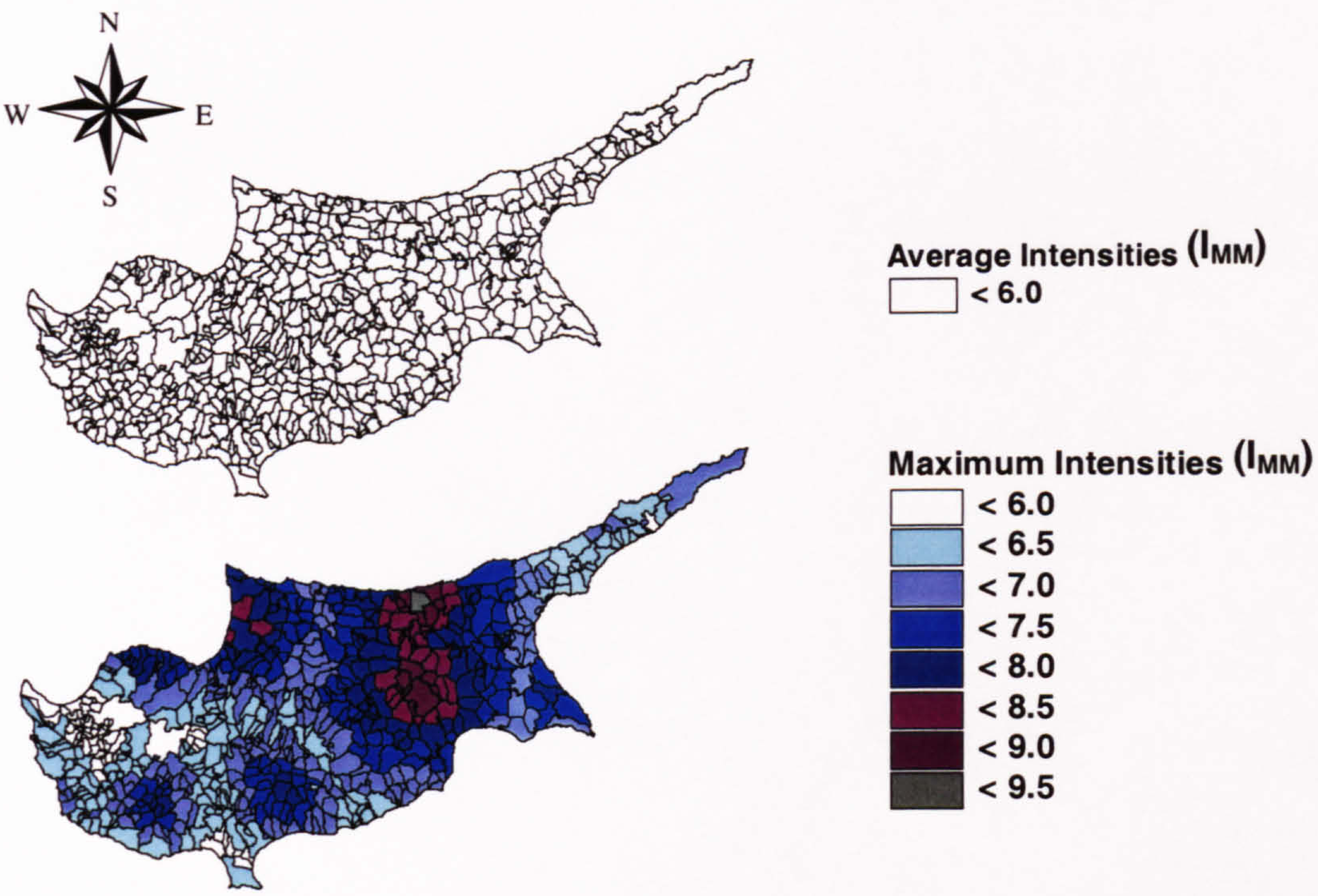


Figure 6.29. Expected maximum intensities and extreme case maximum intensities in 95 years

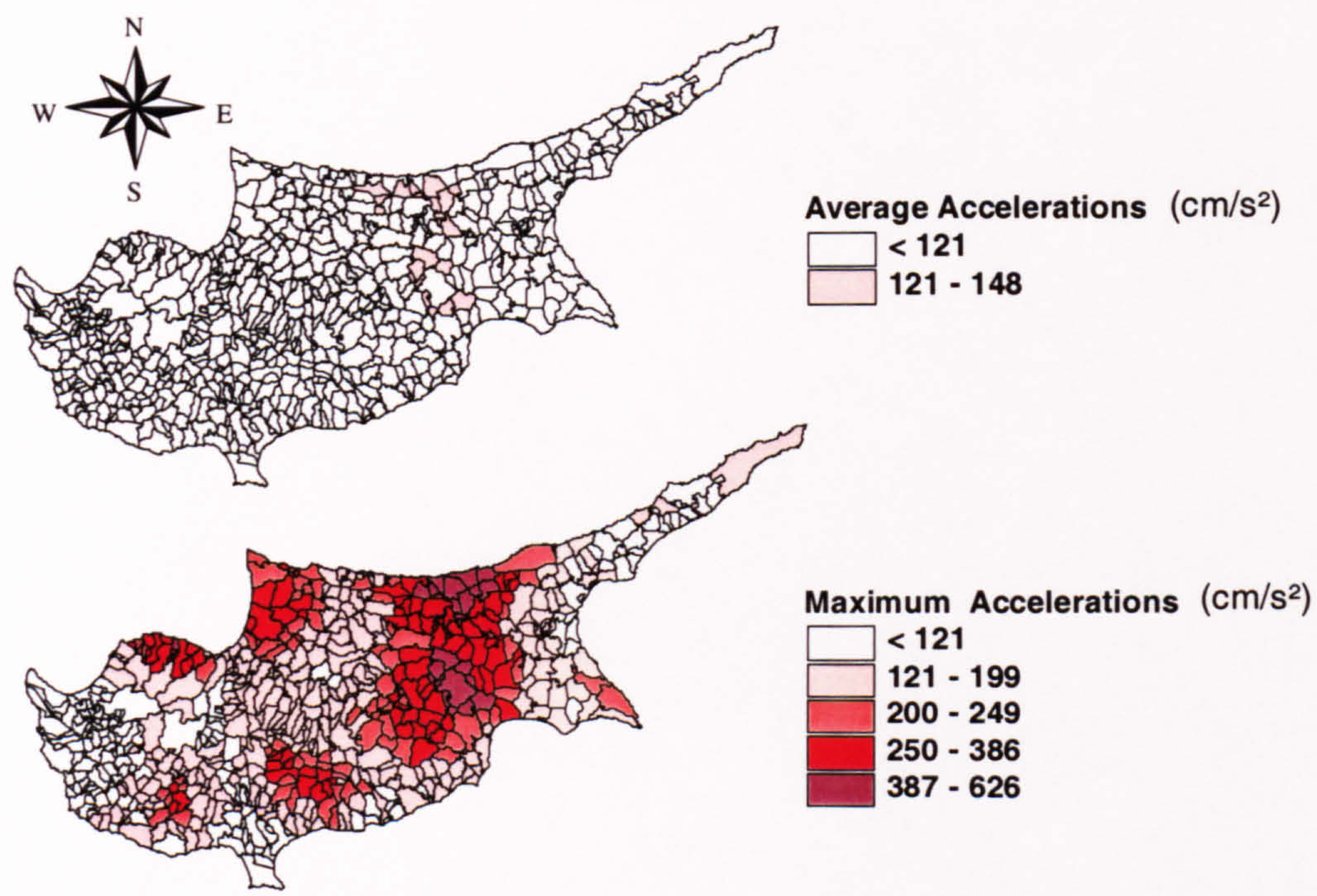


Figure 6.30. Expected maximum accelerations and extreme case maximum accelerations in 95 years

This theory of generating earthquake events based on a recurrence relationship corresponding to the whole area under consideration proved again to be inappropriate for ERA. Despite the fact that the absolute worse case scenario with small possibility of occurrence presented lower intensities and accelerations compared with the results obtained when using Ambraseys (1992) recurrence relationship, they are still not representative of the known seismicity of the island.

Furthermore, the results of this theory are not complying with the earthquake risk, damages, fatalities and injuries estimated based on the historic catalogue of the island.

The main conclusion from this study is that a more detailed and reliable probabilistic hazard model is required for ERA. In the absence of such a model, the historic record gives the best representation of the risk and likely losses.

6.4 RISK MANAGEMENT STRATEGIES

Buildings will never be completely earthquake-proof and societies will never be completely free of earthquake risks. However, the prudent selection of RMS can reduce substantially any potential earthquake risk that can disrupt a whole country.

According to Hays (1994) *"Risk Management suggests that earthquake risk can be controlled within limits set by the community by using all of the options available to the community decision makers and professionals to cope with natural hazards."*

In the following sections various options available for earthquake risk management will be presented and the ones examined for the particular case of Cyprus will be discussed in detail. A flow chart of how the EQ-RACY model deals with RMS is given in Figure 6.31.

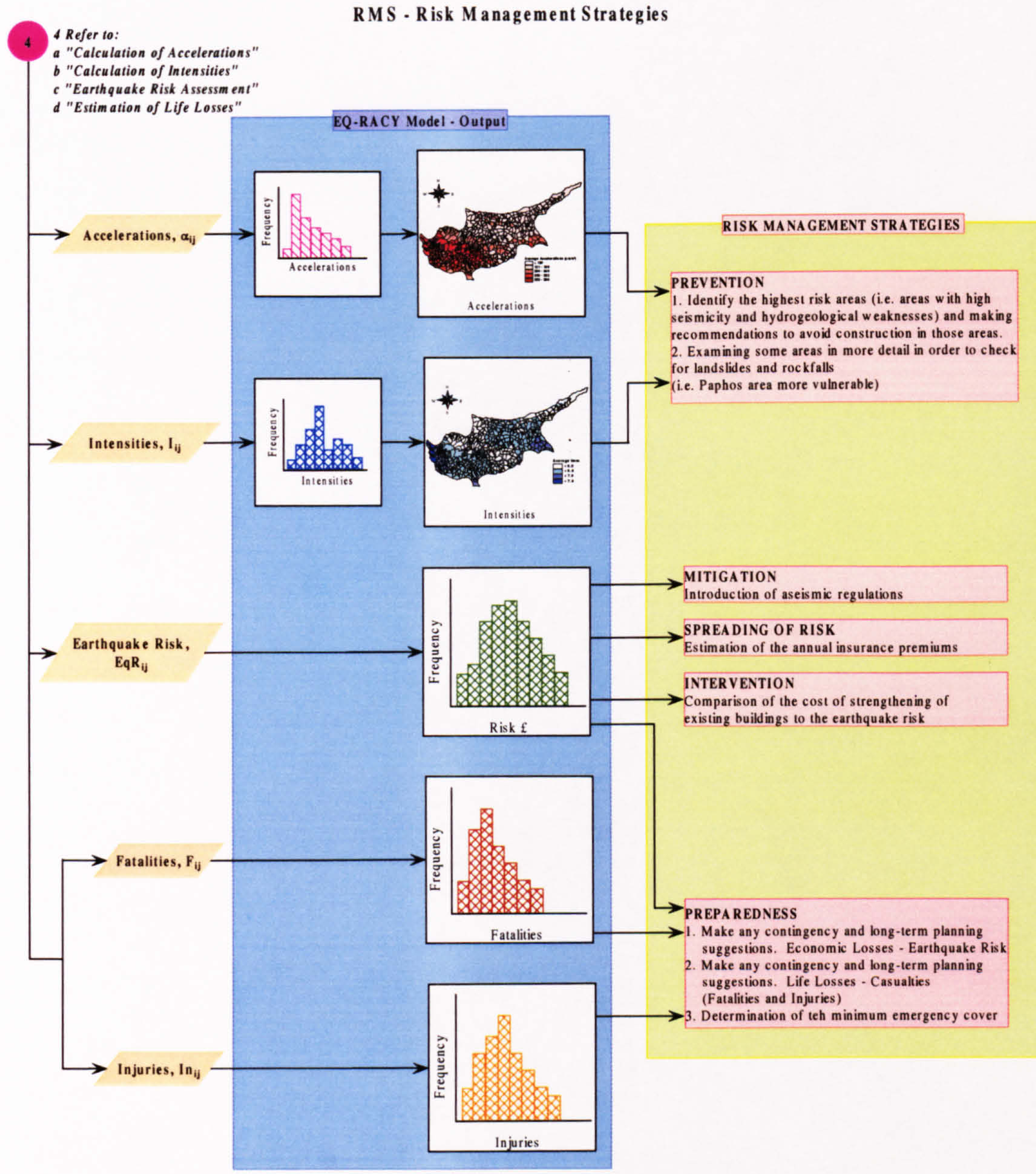


Figure 6.31. General outline of how the EQ-RACY model deals with RMS

PREVENTION

Preventative actions such as macrozonation and planning regulations when taken will reduce the economic and societal cost of earthquakes.

The suggested actions for this option include:

1. Identifying the highest risk areas (i.e. areas with high seismicity and hydrogeological weaknesses) and making recommendations to avoid construction in those areas.

2. Examining some areas in more detail in order to check for landslides and rockfalls (i.e. Paphos area more vulnerable). For areas of highest risk a smaller grid can be used. This can be made in conjunction with microzonation studies.

Whilst the first suggested action was examined and recommendations can now be made, the investigation of the second suggested action can only be undertaken if data are available at the micro-level. However, the proposed framework can be used to undertake microzonation studies through the use of more detailed information and GIS software.

By examining Figure 6.6 and Figure 6.8 it is recommended that microzonation studies are undertaken for all regions with possible maximum intensities of MMI 8 or accelerations of 0.6g.

Planning regulations should aim to prevent construction in highly vulnerable locations, including sites likely to liquefy.

MITIGATION

"Mitigation refers to the actions that reduce the physical and/or social demands or actions that protect community capability" (Hays, 1994).

The suggested actions for this option include the introduction of aseismic regulations.

Aseismic regulations introduced in 1994 introduced what are thought to be arbitrary peak ground acceleration values since they are not based on ERA. It is assumed that these values were determined by modifying the seismic map of Cyprus produced by Neophytou, which indicates the likely maximum intensities. The accelerations (Figure 6.32) were compared to the seismic zone map and maximum values suggested in the aseismic code of Cyprus. The results were surprising as the maximum values suggested by the aseismic code of Cyprus lie well below the expected possible maximum accelerations (g) in a 103 years. The comparison identified critical areas with possible higher risk than the aseismic code of the island suggests.

Hence, it is recommended that the macroseismic zonation of Cyprus is reassessed to become more aligned with the expected acceleration levels (i.e. POE-50% map of Figure 6.32).

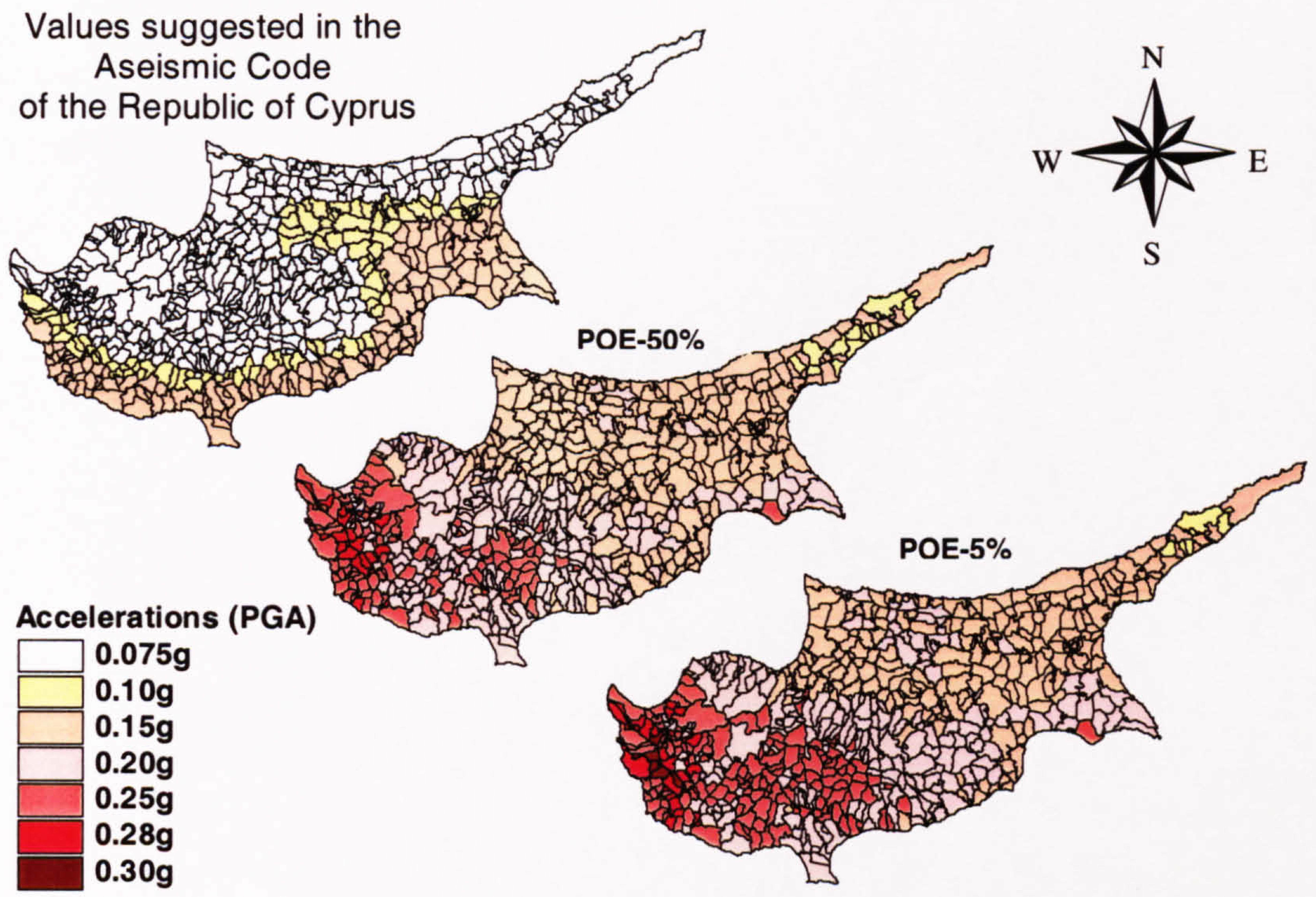


Figure 6.32. Comparison of the maximum acceleration values suggested in the Aseismic Code of the Republic of Cyprus to the estimated maximum accelerations for a 25 year return period

It is also very important for an assessment of the cost effectiveness of these measures to be made, in order to make recommendations as to whether higher or lower peak ground acceleration values are justifiable.

To be able to assess the adequacy of the aseismic code used in Cyprus the cost of the aseismic design has to be compared to the earthquake risk. The design life of a house is considered to be 25 years and assuming that the family houses in Cyprus are usually transferred from the parents to the children a design life of 50 years will also be examined.

The 25 years and 50 years earthquake risk for both POE-50% (50%) and POE-5% (95%) for the whole of Cyprus as well as for the Nicosia municipality were calculated, (Figure 6.33, Figure 6.34, Table 6.4) and compared to the costs of the current aseismic measures for new build constructions.

Table 6.4. Earthquake Risk for 25 Years and 50 Years (in 1996 prices)

	All of Cyprus		Nicosia (Typical RC House £51980)			
	POE-50%	POE-5%	POE-50%	POE-5%	% of buildings value	
25 Years	£613	£1352	£482	£2398	0.93%	4.61%
50 Years	£1211	£1976	£801	£3126	1.54%	6.01%

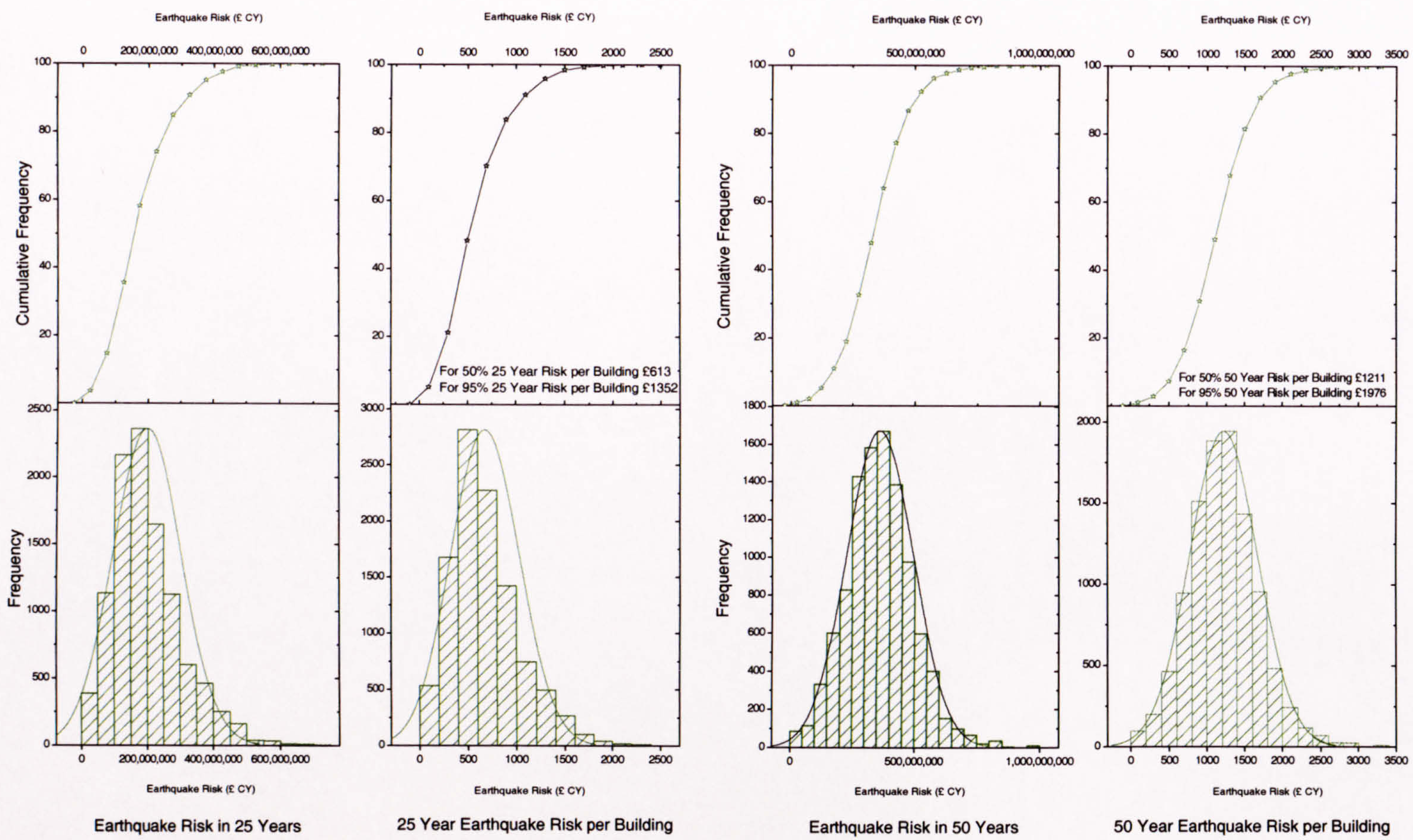


Figure 6.33. Estimated Earthquake Risk for 25 Years and 50 Years per building

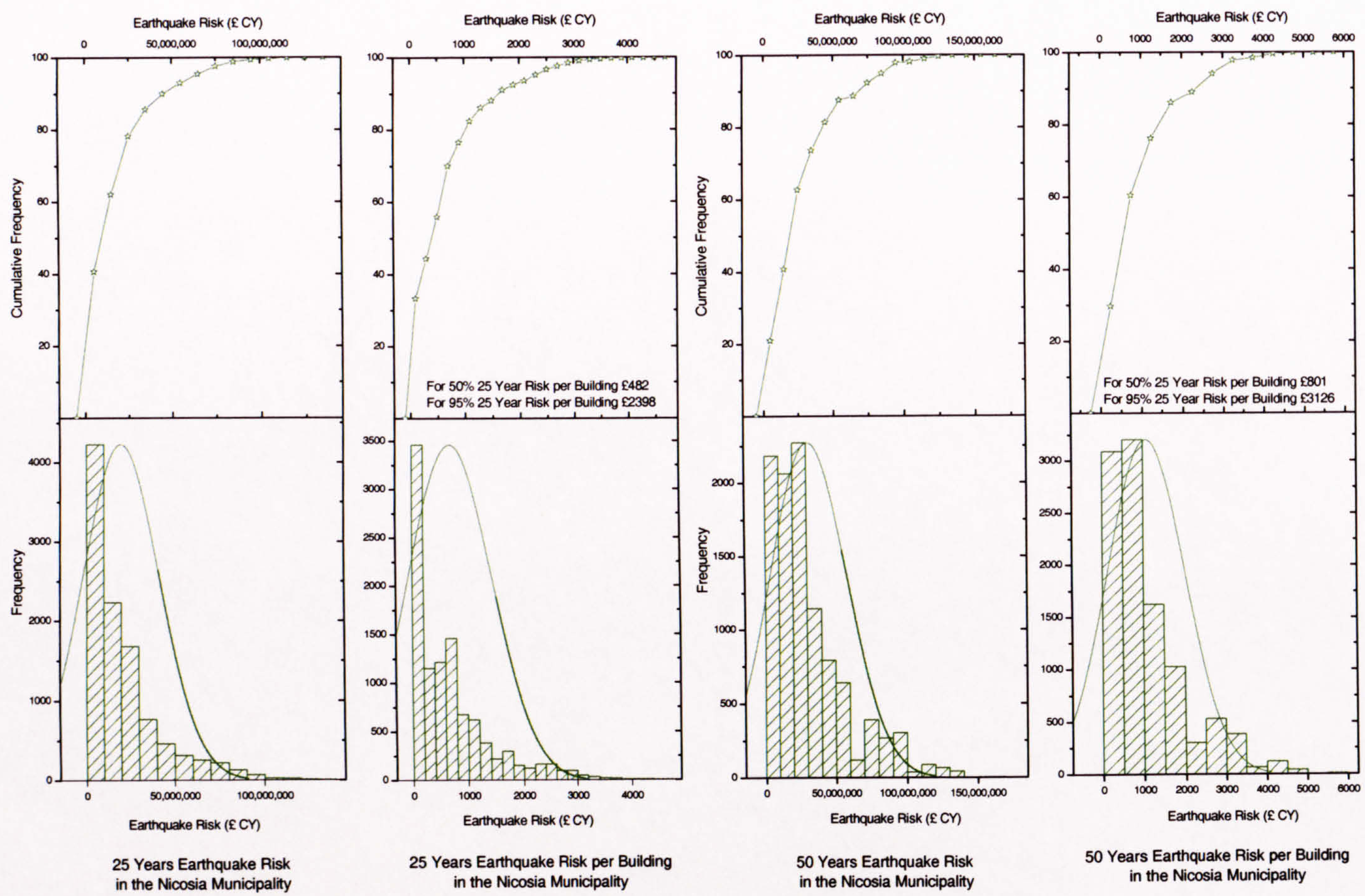


Figure 6.34. Estimated Earthquake Risk for 25 Years and 50 Years per building in the Nicosia Municipality

There is no comprehensive study on the actual cost of aseismic measures based on either the 1994 or the 1986 regulations. However, from discussions with design engineers, Pilakoutas (2000) estimates that the cost of the 1994 aseismic regulations in the region of Nicosia is likely to add 2-4% to the overall building cost.

The average risk for different hazard scenarios

1. Seismic zonation map of Cyprus of maximum intensities (Figure 2.12)
2. Seismic zonation map of Cyprus of design accelerations (map shown in Figure 6.32)
3. Proposed seismic zones (POE-50% map of Figure 6.32)

and different vulnerability levels shown if Figure 6.35,

1. Standard/Substandard(i.e. with no seismic design)
2. Superior buildings with < 4 storeys (i.e. based on the 1994 levels of design)
3. Proposed (i.e. based on design with higher accelerations as shown in POE-50% map of Figure 6.32)

were estimated and compared in Table 6.5.

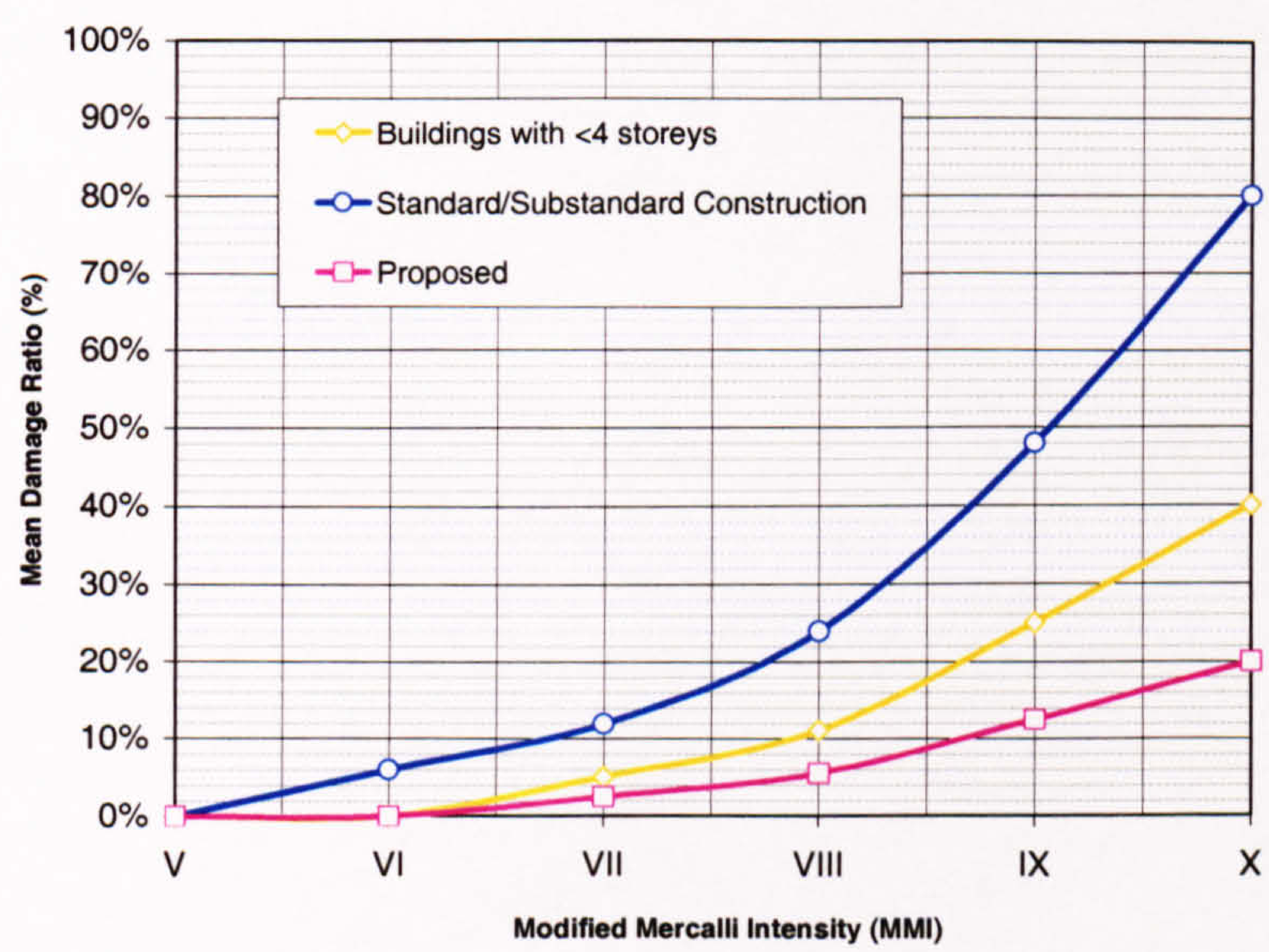


Figure 6.35. Vulnerability curves used in the study of risk

Table 6.5. Average risk for different scenarios

	Max I_{MM}	Amax Aseismic Code of Cyprus	Proposed
No seismic design	£9558	£1029	£4560
With current seismic design	£4338	£0	£1300
Proposed	£2169	£0	£650

The values of Table 6.5 are average values for the entire building stock in Cyprus. It is clear that there is a massive difference between the different hazard scenarios and in particular between the maximum I_{MM} zonation map and the design acceleration map. Since the proposed hazard zonation map is based on historical seismicity it is obvious that the risk predicted by the current design code is too low. In addition, the apparent reduction in risk based on the same code is less than the cost of the code.

On the basis of the original maximum intensity map (which represents a longer time period than for design period) the reduction in risk of £5220 CY is a good value for the £1-2 thousand CY expected investment.

According to the proposed hazard scenario and design accelerations the reduction in risk is £3910 CY, which is equivalent to 8% of the value of the building. The new accelerations are naturally going to increase the cost of construction but only by an estimated 3%-5%.

Additional benefits of buildings designed for earthquakes include more robustness and less susceptibility to subsidence. The increased robustness means that buildings are less likely to suffer accidental damage (such as due to impacts or partial collapse under exceptionally high loads) not in combination with earthquake loading.

Hence, in conclusion it can be said that the aseismic measures proposed enhance the quality of construction and their cost is less than the reduction of seismic risk, but with extra benefits for reduced vulnerability to other threats as well.

Spreading of Risk

The suggested actions for this option include the estimation of the annual insurance premiums.

The current annual premiums for earthquake cover were obtained from various Insurance companies in Cyprus. Whilst the earthquake cover is usually offered in conjunction with fire cover and water damage cover (i.e. pipelines breaking), it can also be requested on its own. The premium rates are shown in Table 6.6. The type of construction does not matter if the insurance taken is only for earthquake protection. However, if the insurance includes also fire and water damage cover then the type of construction is taken into consideration. As far as the location of the building is concerned, it is not important. The average annual earthquake risk per building is presented spatially in Figure 6.36. Figure 6.37 presents the average annual earthquake risk per building in the five Districts. The prices shown are the annual earthquake insurance costs for each area based on the corresponding building value and a premium of £0.60 per £1000.

Table 6.6. Annual premiums for earthquake cover by various insurance companies in Cyprus

Name	Premium per £1000	Excess % of building value
Ecclesiastical	£0.70	1.5 %
Cosmos	£0.60	1.5 %
Laiki	£0.60	1.5 %
Alpha	£0.60	1.5 %
GAP Vasilopoullos	£0.50	1.0 %

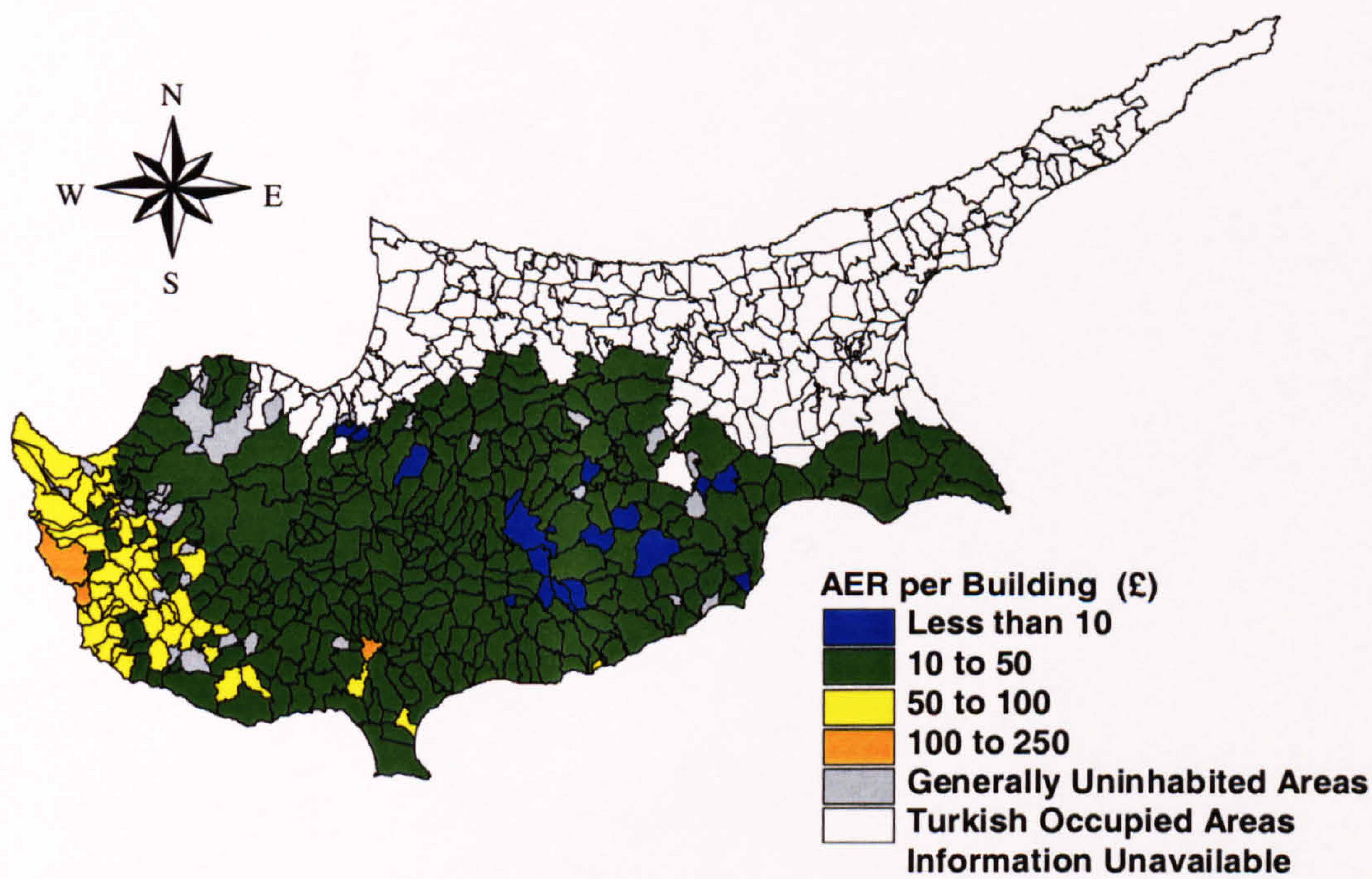


Figure 6.36. Average Annual Earthquake Risk per Building

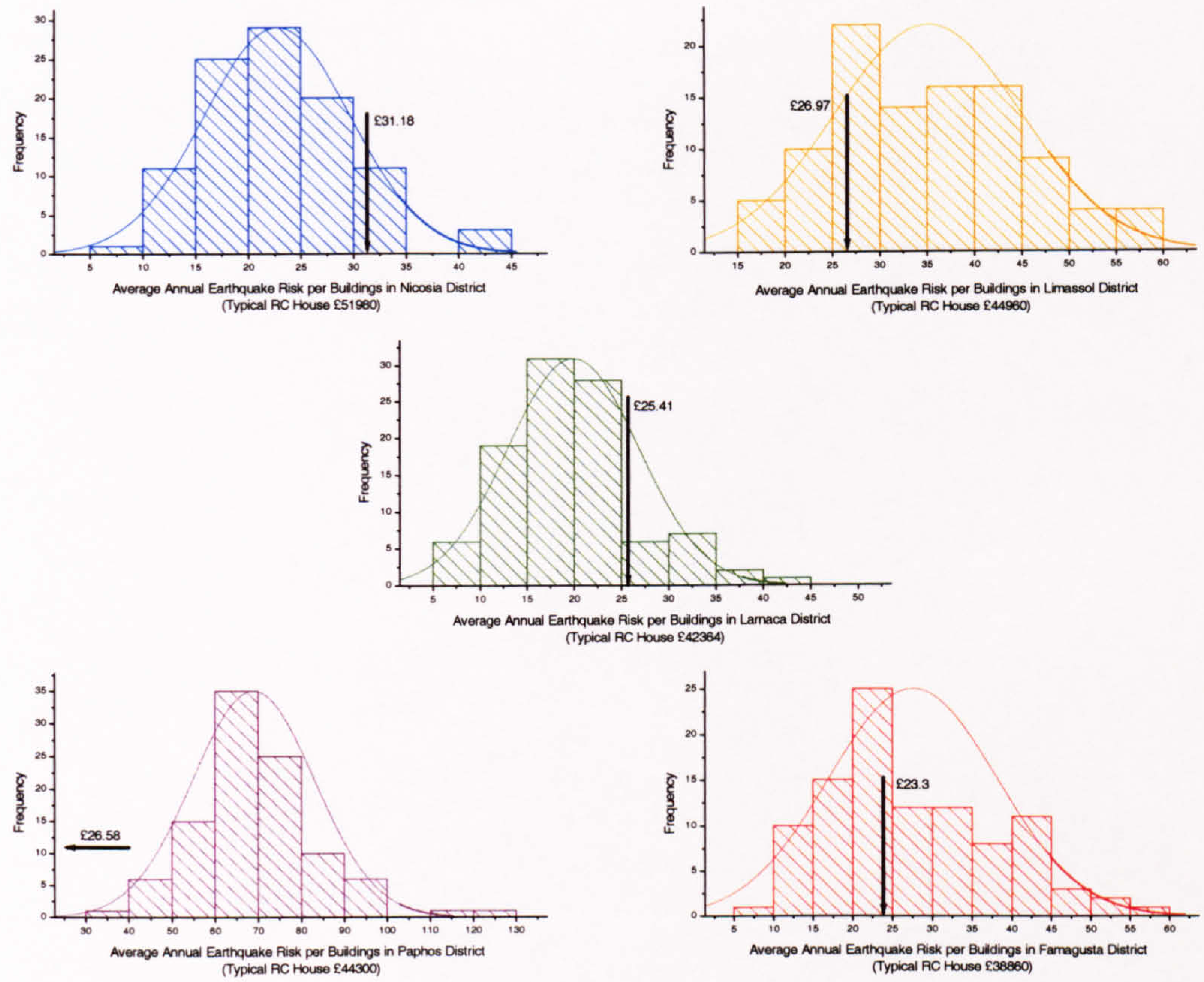


Figure 6.37. Average Annual Earthquake Risk per building in the five Districts

By examining Figure 6.37 it is apparent that whilst the insurance premiums in Nicosia and Larnaca are conservative the opposite applies to Limassol and Famagusta. Furthermore, a premium completely unrepresentative of the seismic risk is suggested for Paphos. Though the insurance premiums overall reflect the seismic risk very well, their insensitivity to the vulnerability and exposure of the buildings makes them not so prudent.

A revaluation of the premium rates for the whole island should therefore be undertaken taking into consideration the particular risk of each area. Nonetheless, since the actual insurance premiums appear to be fair, it is advisable for the government to make earthquake insurance mandatory for all new buildings and hence, reduce the exposure of the state against this risk.

INTERVENTION

"Intervention refers to the actions taken while the physical effects of the natural hazard are still developing in order to lessen the expected physical and/or social demands or actions that lessen the expected impacts on community capability" (Hays, 1994).

The suggested actions for this option include the comparison of the cost of strengthening of existing buildings to the earthquake risk.

For the case of strengthening, Koronida (2000) selected and analysed three typical samples of buildings:

- a four storey building constructed in 1985 in Nicosia,
- a ground floor house constructed in 1980 in Nicosia which was extended and transformed to a three floor building of two houses in 1998 and
- a two storey building of two houses constructed in 1963 in Nicosia and refurbished in 1997.

These buildings were selected due to the fact that they represent the typical building stock in Cyprus. The majority of the multi-storey buildings in Cyprus are around 4 floors. 70% of the houses in Cyprus were constructed between 1960-1980. More specifically, 13% of the houses were constructed during the 1960s, 27% during the 1970s and 30% during the 1980s.

From the study it was established that, in general, the cost of aseismic strengthening depends on the type of the building. The various costs and percentages are presented in Table 6.7. A building like the four storey block of flats examined can be adequately strengthened at a cost of just 4% of the total cost of rebuilding.

On the other hand to strengthen a building like the two-storey house constructed in the 1960s, the total strengthening costs will rise to 10% of the total cost of rebuilding. This is mainly due to the fact that the occupants will have to be re-housed during the period of strengthening which adds the extra cost of rent etc.

Finally, for buildings that are to be extended vertically, the cost of a relatively adequate aseismic strengthening is of the order of 2% of the total cost of rebuilding.

Table 6.7. Cost of aseismic strengthening for a selection of buildings

	Type of Building	Year	1st approach part strengthening Cost	% of rebuilding Cost	2nd approach total strengthening Cost	% of rebuilding Cost
1	4 storey building	1985	£11000	4%	£32000	12%
2	ground floor house	1980	£15000	10%		
	extended and transformed to a three floor building of two houses	1998				
3	a two storey building of two houses refurbished	1996 1997	£977	1.4%	£2000	2.6%

Therefore, the general conclusion is that in the cases where there is no intention of making any changes (extensions, refurbishment etc) in the building, besides the direct costs of the strengthening there are indirect costs, which depend on the use of the building. Hence, for the average building, unless the intention is to modernise the building and extend its life significantly, the cost of strengthening exceeds the reduction in risk.

In the cases where existing buildings are either extended or refurbished then the cost of aseismic strengthening is relatively small compared with the value of the investment, and hence, should be encouraged or even be made mandatory by law. Koronida (2000) proposed the introduction of tax incentives to encourage strengthening.

In the future, the EQ-RACY model can be modified to accommodate a more detailed representation of the structural vulnerability and with further analysis of the results, the studies can reveal what are the approximate levels of structural strengthening necessary for different structural systems and for structures of varying importance. The appropriate retrofitting could therefore reduce the risk of damage to buildings with high vulnerability.

PREPAREDNESS & EMERGENCY RESPONSE

"Preparedness refers to the actions that anticipate and reduce the physical and/or social demands or actions that enhance and protect community capability" (Hays, 1994).

"Emergency Response refers to the actions that define the expected physical and/or social demands or actions that manage and reallocate community resources to protect community capability" (Hays, 1994).

The suggested actions for this option include:

1. Make any contingency and long-term planning suggestions. Economic Losses – Earthquake Risk
2. Make any contingency and long-term planning suggestions. Life Losses – Casualties (Fatalities and Injuries)
3. Determination of the minimum emergency cover

For the purposes of this research only the first two actions are examined.

ECONOMIC LOSSES – EARTHQUAKE RISK

From the results of this ERA the damage, over a specified period of time (e.g. 25 years) and for a specific probability (i.e. POE-50%) can be determined.

In the long-term the government must save or invest an equal amount to the annual average earthquake risk for each year until the total amount to cope with serious earthquakes is reached. According to the results of this research (Figure 6.38) the annual average earthquake risk is £9,054,440. This figure shows the mean values, the standard deviation (σ), the POE-50% (50%), the POE-5% (95%) and the POE-1% (99%).

As far as contingency planning is concerned, for a 10 year period, the results (Figure 6.39) showed that the average earthquake risk (i.e. POE-50%) over that period is £82,429,160. If the value with a POE-5% (95%), is to be taken into consideration the earthquake risk reaches £242,338,000. The government can reduce contingency planning fund if it makes it clear to building owners that they are entirely responsible for the seismic risk and hence, only plans for public buildings, utilities and infrastructure. In that case, earthquake insurance should be made mandatory.

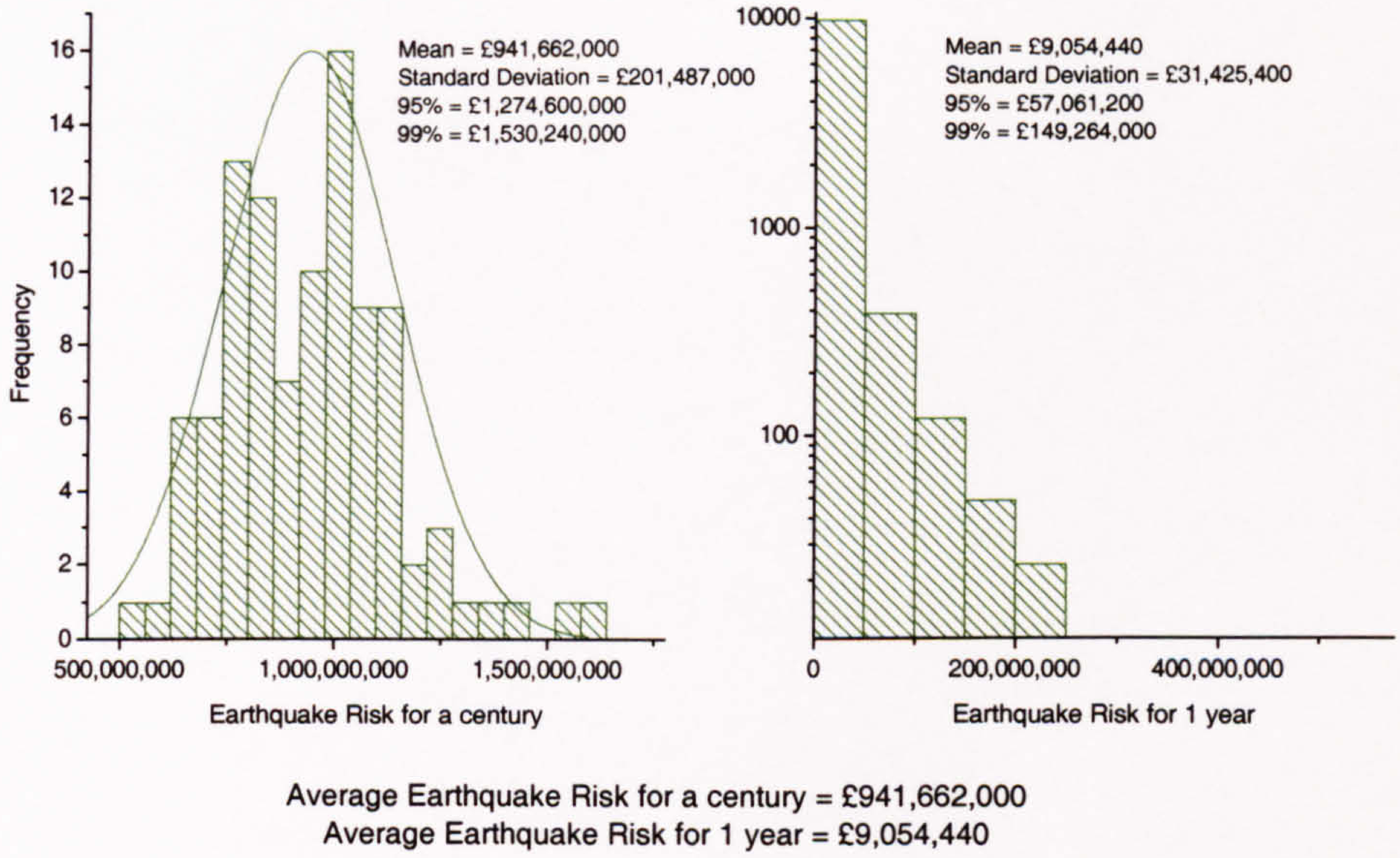


Figure 6.38. Long-term Plan Suggestions

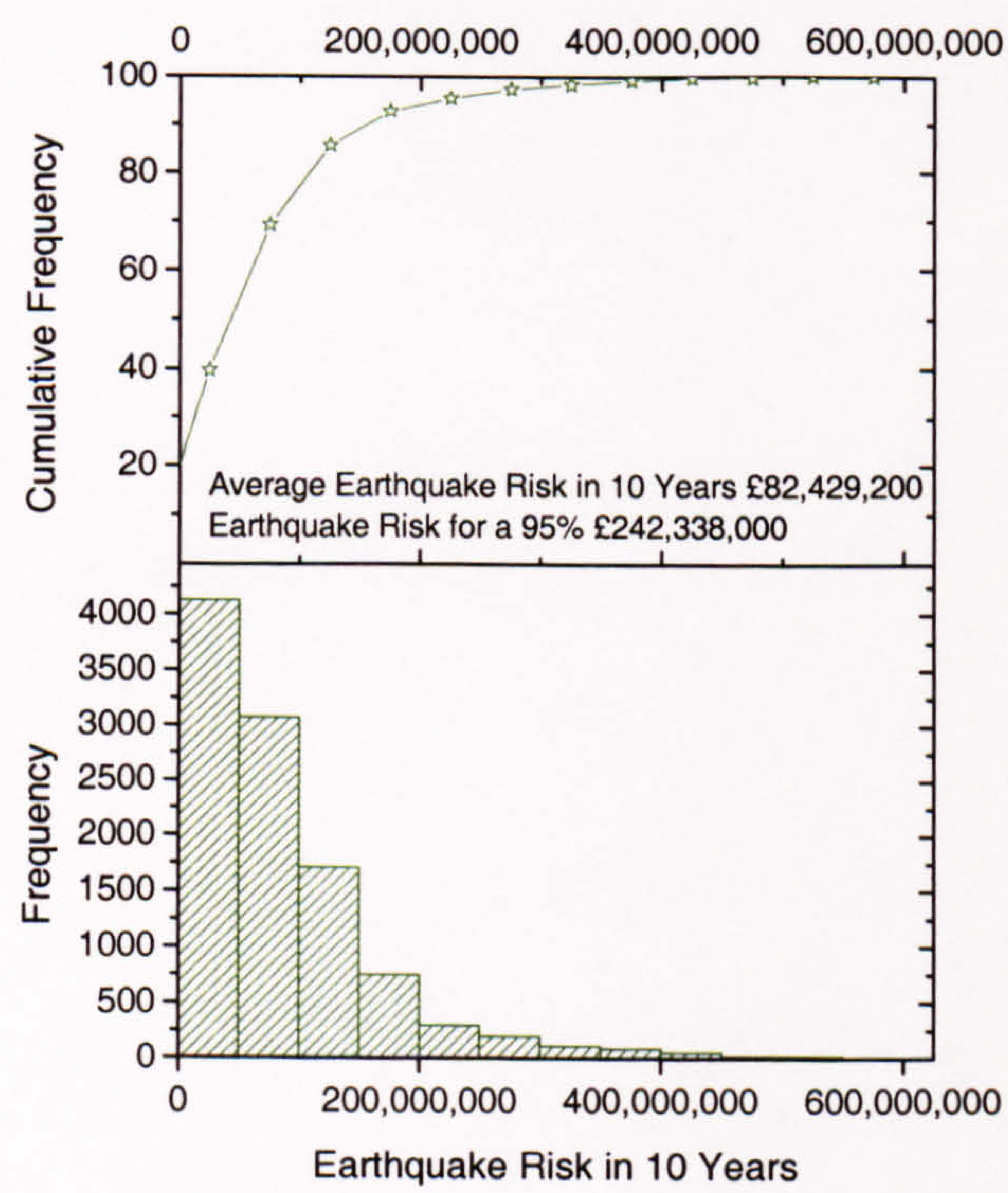
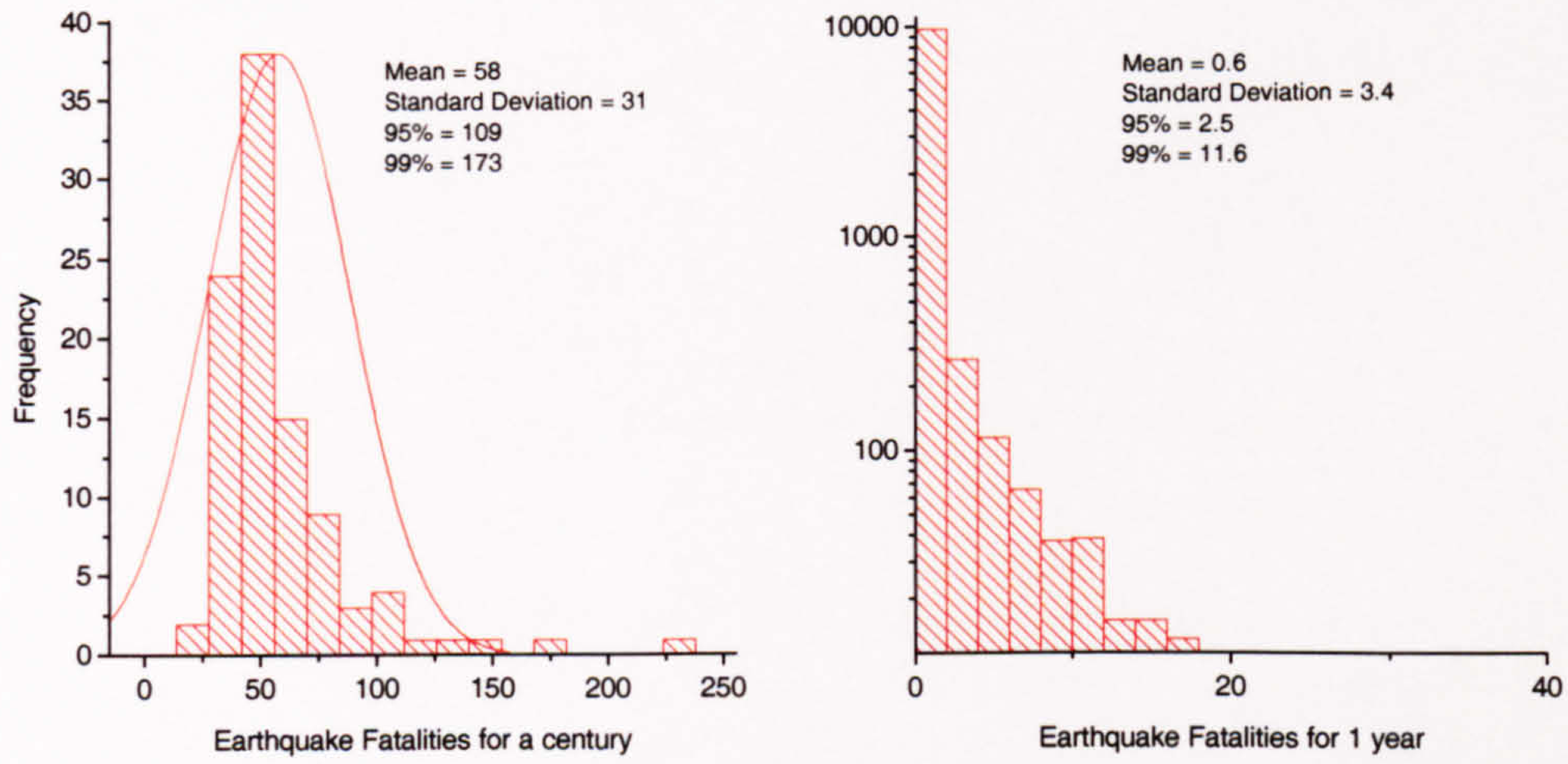


Figure 6.39. Contingency Plan Suggestions

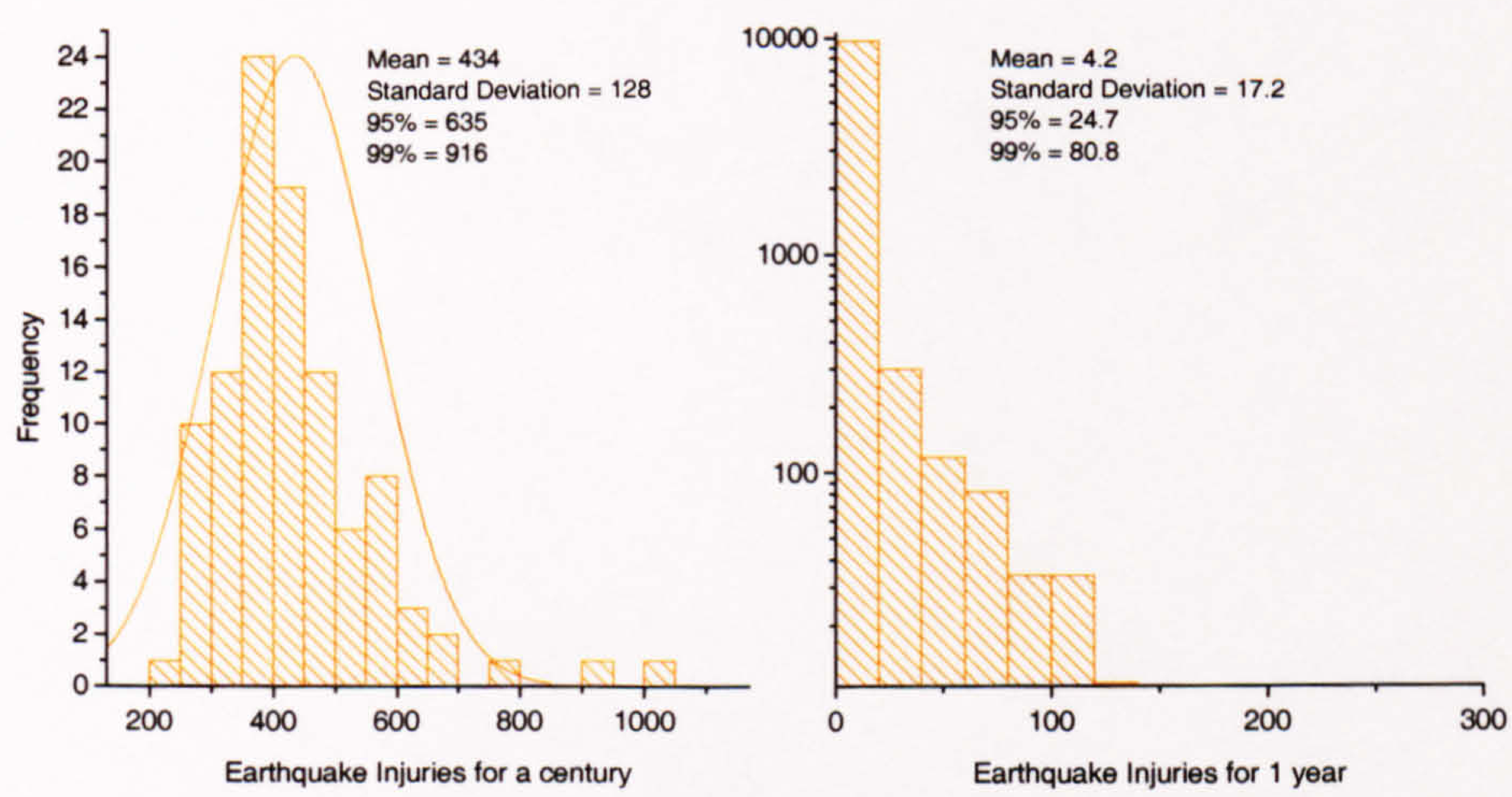
LIFE LOSSES – CASUALTIES (FATALITIES AND INJURIES)

In an attempt to suggest some preparedness actions, which would assist in the way emergency services cope after any possible earthquakes, it was decided that the earthquake fatalities and injuries should be examined. The results obtained regarding the life losses are presented in Figure 6.40 for fatalities and Figure 6.41 for injuries. These figures show the mean values, the standard deviation (σ), the POE-50% (50%), the POE-5% (95%) and the POE-1% (99%).



Average Earthquake Fatalities for a century = 58
Average Earthquake Fatalities for 1 year = 1

Figure 6.40. Centennial and Annual Average Earthquake Fatalities



Average Earthquake Injuries for a century = 434
Average Earthquake Injuries for 1 year = 4

Figure 6.41. Centennial and Annual Average Earthquake Injuries

The mean values are rather small. Hence, an estimate of the likely losses in a single year (with POE-1%) is required. From these figures it is clear that the emergency services should be able to cope with around 81 injuries (POE-1%) as a result of a severe earthquake. Studies involving return periods of 10, 25 and 50 years estimate injuries with a POE-5% of 131, 218 and 374 respectively.

It is anticipated that the island's emergency services working together with the civil defence would be in a position to cope with such numbers. Groups of Cyprus fire fighters have already been trained in search and rescue techniques in the United States. However, their participation in search and rescue exercises or missions would improve their training.

STATE OF ECONOMY

A RMS depends very much on the current and predicted economic state of the country. Different models could be examined to enable decision-makers to decide on the appropriate RMS. For example, if Cyprus joins the European Union and the union has a co-ordinated disaster relief programme then the preparedness and emergency response will change appropriately. This research does not address this option, however, its full investigation is advised for the future.

6.5 CONCLUDING REMARKS

With the imminent accession of Cyprus in the European Union the possible solution of the Cyprus Problem and the extensive reconstruction programs that would ensue, it is essential that construction and land-use practices employ modern knowledge and methodology. Failure to do so together with the active seismicity of the area could create devastating results.

The suggestions/options for RMS must therefore be considered and where necessary further studies should be undertaken. A modest investment in the study and application of these RMS would result in reductions of future life or economic losses.

Nevertheless, the results of this assessment should not be regarded as complete. It must be mentioned that they only take into account the buildings involved in this study. The current ERA does not include much of the infrastructure, the cost of human loss or loss due to interruption of business or social functions.

CONCLUSIONS
&
RECOMMENDATIONS FOR FUTURE WORK

7.1 INTRODUCTION

The aim of this study was to develop an ERA framework, which incorporates the spatial aspects of seismic hazard and risk evaluation and to apply the framework to the island of Cyprus by producing spatial models for seismic hazard, building and population density, vulnerability, and geology that would enable the assessment of various RMS. To attain this aim, the parameters involved for the estimation of risk were initially investigated separately and then their collective effect was examined by utilising probabilistic earthquake risk assessment (PERA). Thus a substantial number of numerical simulations was performed using the Monte Carlo simulation method.

All initial objectives were achieved over the course of this work. The following general conclusions are drawn and related to each initial objective (O1, O2, O3) and suggestions for future research are given.

7.2 CONCLUSIONS

O1 PERA is a complex process, whose success is dependent on many aspects. One of the most important aspects is the probabilistic modelling of all basic variables, which requires the use of appropriate statistical data. Though this exercise was undertaken, it was found that there is lack of comprehensive statistical data for many of the basic variables considered, such as magnitude, depth, epicentre location, etc.

O1 A new non-conventional PSHA method was adopted in the model for the first time. This method utilises the historical record compiled by this study as the basis of hazard modelling rather than using a homogenous distribution of seismic activity. However, the earthquake magnitude and location as well as their effect was modelled probabilistically, simulating the uncertainties involved.

O2 The historical record was compiled by merging records from various sources (Ambraseys, 1992; IPRG, 1995; Solomis, 1998; Gajardo et. al., 1998). This merge was undertaken by converging all data into a single magnitude scale (M_S).

The historical record revealed that the distribution of earthquakes in space is not random as assumed by recurrence equations (such as Ambraseys, 1992) but more associated with the tectonics of the island, which are dominated by the Cyprian Arc. New recurrence relations were developed by dividing the island into three regions. Furthermore, the total seismic energy release was also examined. This has shown that the distribution of the energy release is also not uniform, with sudden releases of energy occurring approximately every 25 years.

O2 Finally, the depth of the earthquakes was examined and again it was found that there appears to be a trend with shallower earthquakes occurring near the south coast of the island.

O2 Two approaches to seismic hazard determination were proposed and tested for their applicability in the assessment of the earthquake risk. It was concluded that without a spatial distribution model, such approaches are unsuitable for ERA. A more detailed and reliable probabilistic hazard model is required for ERA and in the absence of such a model, the historic record which is used in the proposed framework, gives the best representation of the risk and the consequential losses.

O1,2 Data and models regarding various input parameters, such as vulnerability, cost, as well as fatality and injury ratios, had to be assumed and crude ways of approaching these aspects were adopted. This was necessitated due to the lack of adequate data, however, verification studies showed that despite the crudeness of these approaches relatively accurate losses were predicted. The simplifications made for some of the models do not pose a major problem in the development of the model since the aim was not to develop a 100% accurate model, but a model capable of dealing with the relevant input data, predicting and suggesting solutions and management strategies.

O1,2 The choice of attenuation equations is also crucial in ERA. The chosen equations (Theodulidis and Papazachos, 1992) were shown to work very well, simulating the effect of recent well documented earthquakes appropriately. However, more suitable equations are required for relating ground accelerations to intensities.

O1,2 The attenuation of the seismic waves is also affected by the geology and this effect was also taken into account. However, despite expectations, the sensitivity studies on the effect of geology did not show a major effect on risk. Naturally, this is not true at the micro level, but at the macro level this appears to be a fair conclusion.

O1,2 The next parameter of importance is the building vulnerability. Due to the absence of any data on the buildings of Cyprus, general vulnerability relations were adopted which are based on MMI. This meant that attenuated accelerations had to be converted into intensities. Though this adds to the uncertainty, it is not thought to have affected the results in a negative manner.

O2 Several assumptions were made on the building and population distribution. Again these are not expected to have influenced the results by much, and when more information becomes available they can be taken into account more accurately.

O1,2 The models used, for the expected injuries and fatalities, will almost certainly need further calibration.

O1 The use of a digitised map for the visualisation of the results proved to be a useful tool. Furthermore, the use of detailed databases with a common reference point facilitated the smooth operation of the model.

O2 A large number of numerical simulations was performed by determining earthquake series using the Monte Carlo simulation method and the resulting loss distributions were then employed in various comparisons.

Various RMS were examined and recommendations to the relevant governmental departments of Cyprus can now be made.

Prevention

O3a Due to lack of time it was not possible to process all the results in order to develop probabilistic models for expected accelerations in all regions for all periods of time. However, simplified equations were developed based on the data from the 4 main municipal areas. These equations were used to develop a map of design accelerations. It is clear that these accelerations are higher than the ones currently used by the seismic code. This is despite the fact that the maximum intensities map on which the seismic zonation is based agrees well with the maximum intensities predicted by the model.

Preparedness & Emergency Response

O3e The average annual risk is just below £10 million CY and the average risk per building is £31 just below the average insurance rate.

Mitigation

O3b The predicted maximum and average intensities and accelerations were found to differ considerably from the seismic map of Cyprus. This appears to be a result of the effect of geology as well as due to the fact that the hazard map is supposed to reflect design values (i.e. POE-5%).

The 1994 design acceleration seismic zonation was found to underrepresent the expected accelerations and a new map is proposed based on a POE-50% for a period of 25 years.

The assessment of the cost effectiveness of the aseismic code (1994) of Cyprus was undertaken and was found that though the hazard is underestimated, the measures are still cost effective. In addition aseismic measures improve the quality of construction, hence, reduce the vulnerability to other hazards.

The assessment of the cost effectiveness of the proposed design accelerations was also examined and were found to reduce the risk by about 8% of the building value at a cost of around 3-5%.

Spreading of Risk

O3c A study of the earthquake cover offered in Cyprus identified that overall the insurance premiums reflect the seismic risk very well, however, their insensitivity to the vulnerability and exposure of the buildings make them not prudent. Furthermore, the actual premium rates appear to be fair, so it is proposed that the government should make earthquake insurance mandatory for all new buildings in order for the exposure of the state against earthquake risk to be reduced.

Intervention

O3d A comparison of the cost of strengthening of existing buildings to the earthquake risk concluded that for the average building the cost of strengthening exceeds the reduction in risk. However, in the case where the intention is to modernise the building and extend its life the cost of aseismic strengthening is relatively small compared to the value of the investment and should be encouraged (by tax incentives) or made mandatory.

Preparedness & Emergency Response

O3e Finally within the long-term planning of the government an amount of just below £10 million CY, equal to the annual earthquake risk, should be either saved or invested every year. For contingency planning for a 10 year period for a POE-5% the amount rises to just below £250 million CY. However, making earthquake insurance mandatory will reduce this value.

As far as life losses are concerned the values (81 injuries with POE-1%) suggest that the emergency services working together with the civil defence should be in a position to cope adequately.

7.3 SUGGESTIONS FOR FUTURE WORK

Whilst this study met successfully its aims and objectives, it has also identified areas that require future work and opened new topics for investigation such as:

- Hazard models which take into account the spatial and temporal distribution of events need to be developed.

- Attenuation equations should be developed specifically for the island of Cyprus. A grid of accelerometers needs to be established in the island to collect the necessary data.

- Future work should involve the study of other risks such as landslides and tsunamis besides the risk of direct structural damages due to ground shaking. The detailed examination (i.e. use of smaller grid) of areas under specific threats such as landslides and tsunamis will reduce the economic and societal losses from the secondary effects of future events.

- More detailed information regarding the vulnerability of the building stock and its distribution and value should be collected and included in the model, which would enable better predictions. The model EQ-RACY can be modified to accommodate a more detailed representation of the structural vulnerability. Further analysis of the results can reveal the required levels of structural strengthening (retrofitting) for different building types and structures of varying importance, therefore reducing the risk of damage of highly vulnerable buildings.

- Future work should concentrate in developing vulnerability relations based on expected ground accelerations.

- The proposed framework could be extended to undertake microzonation studies through the use of more detailed information and GIS software, which will enable the better representation of the input data. Therefore, existing maps of population statistics and hydrogeology, for example could be readily incorporated into the framework. Furthermore, relevant geophysical parameters (including soil thickness, rock stiffness and topography) could be modelled as uncertain input variables within the GIS simulation framework. In addition to that the calculation of emergency response times in the event of a natural disaster could also be accommodated by the use of a GIS.

- The full investigation of the current and predicted economic state of Cyprus so that different models could be examined to enable decision-makers to decide on the appropriate risk management strategies is also suggested for the future.

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APPENDIX A
Supplementary Information for the Literature Review

SUPPLEMENTARY INFORMATION FOR THE LITERATURE REVIEW

This appendix provides general background information on various aspects presented in chapter 2.

1 EARTHQUAKES

1.1 SEISMOLOGICAL ASPECTS

The earth is made up of 3 main layers: the Crust or Lithosphere, the Mantle and the Core. There is evidence that the earth's crust is moving in vast, rigid sections or "tectonic plates" (Figure A-1) (Richter, 1958; Dowrick, 1987). These plates are thought to float on the plastic upper mantle and their movement is away from or against one another (Figure A-2). This movement is driven by convection currents in the mantle as a result of the temperature differences between the earth's core and crust. During this movement, tensile, shear and compressive stresses are created between the plates. The build-up of stresses reaches a maximum limit, after which fracture occurs. With the breaking of the earth's crust there is a catastrophic release of elastic strain energy. This strain release is the cause of major earthquakes and may result in a fault appearance, rockfalls, landslides or other land failures or tsunamis (see section 1.2).

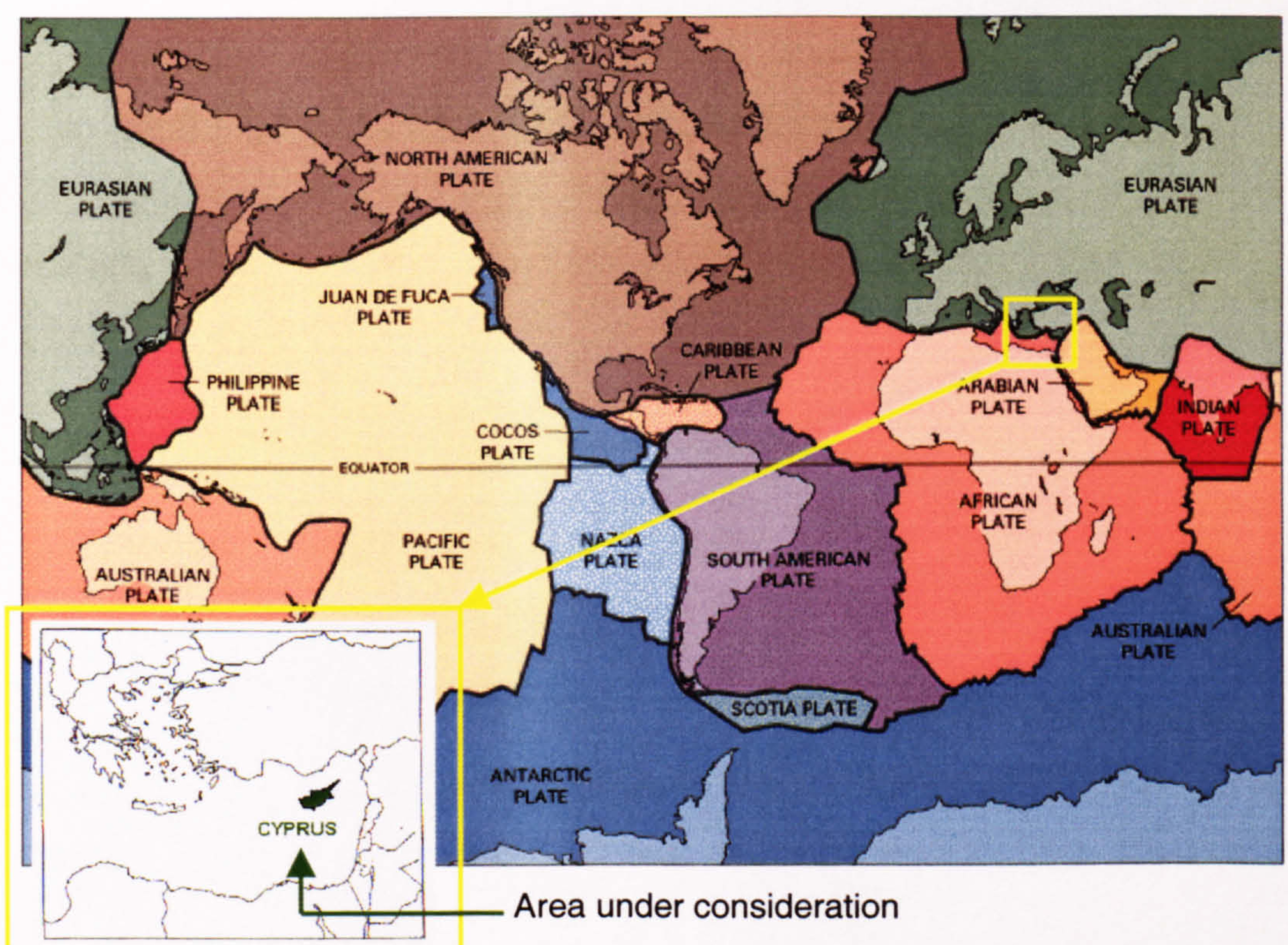


Figure A-1. Major Tectonic Plates of the Earth (after Fraser and Watson, 1997)

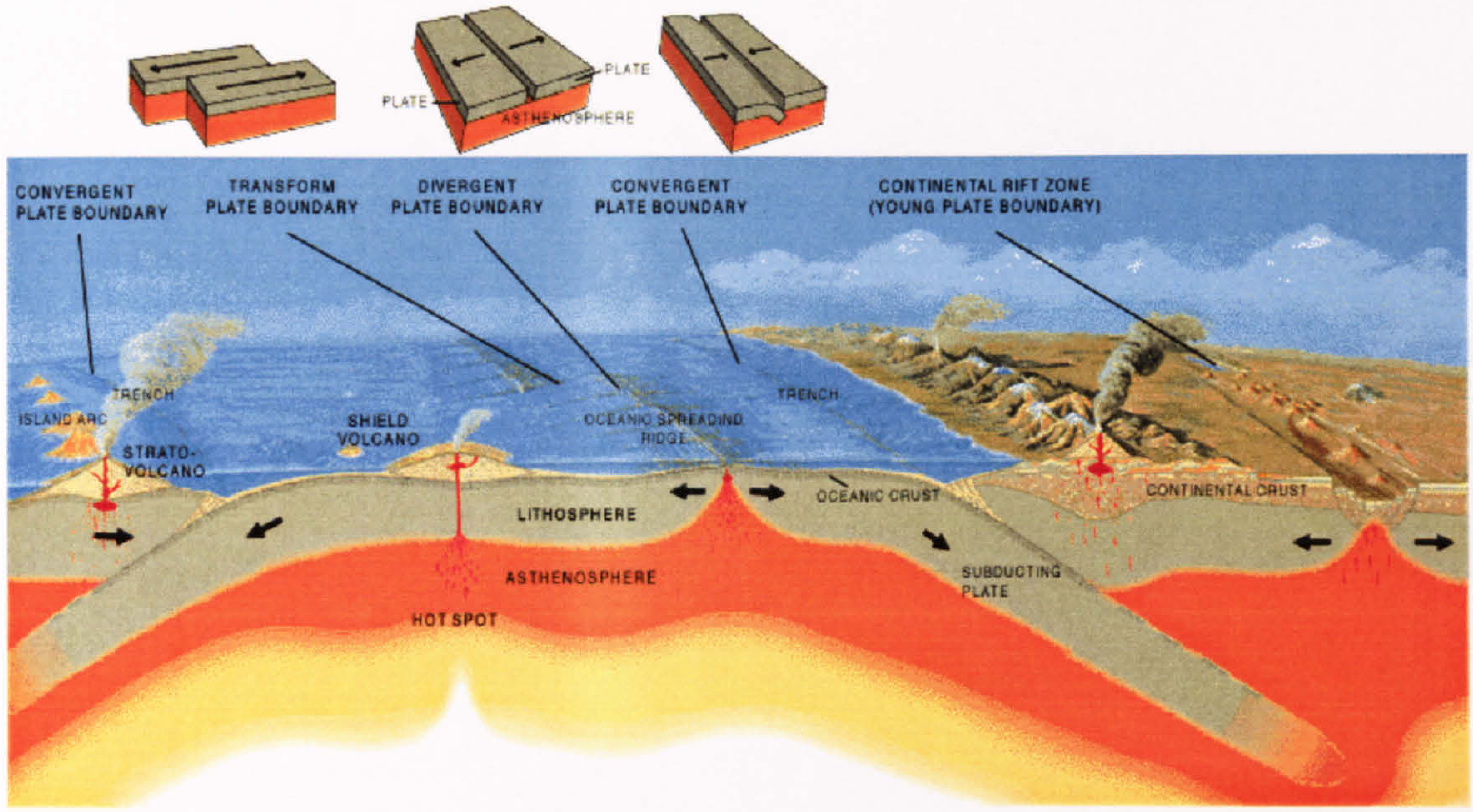


Figure A-2. The main types of tectonic plate boundaries (Kious and Tilling, 1996)

The elastic strain energy release initiates at one point (hypocentre or focus) (Figure A-3) and afterwards spreads out over the rupture surface rapidly. Failures normally occur along a surface of least resistance and that is why the same faults tend to move repeatedly.

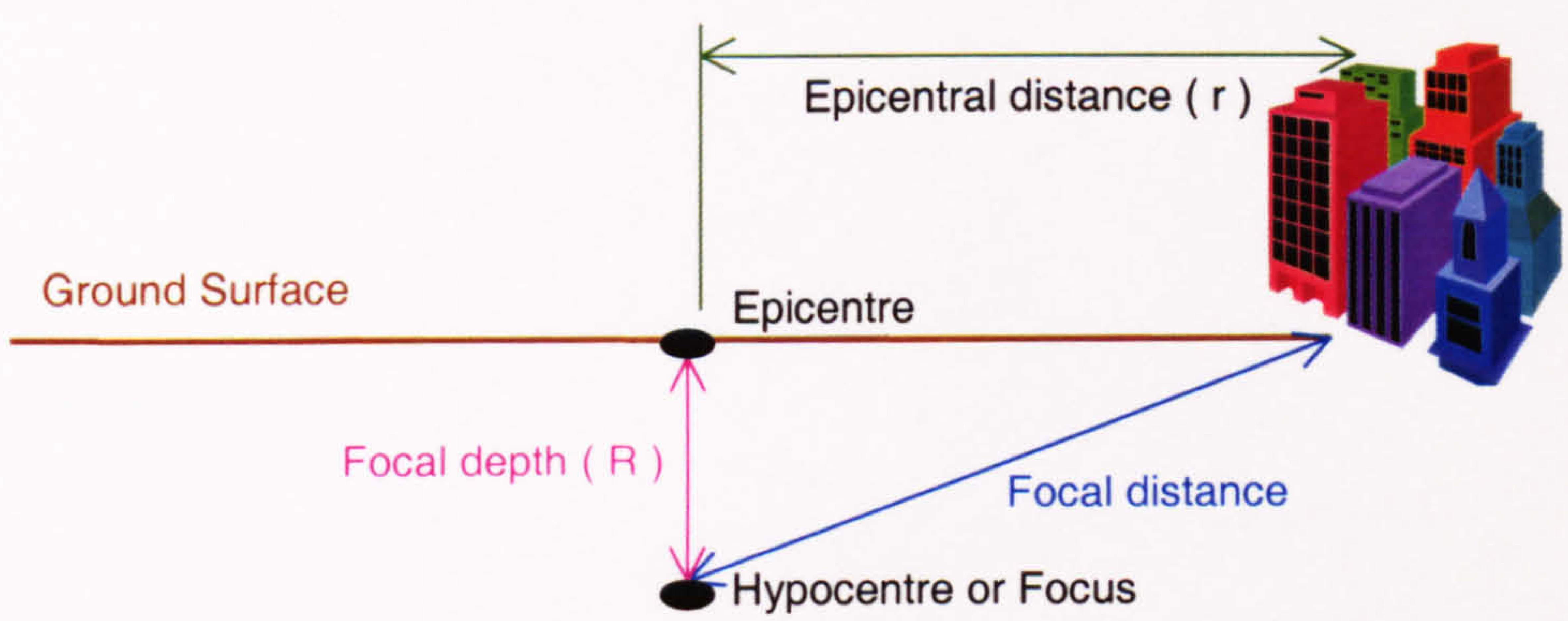


Figure A-3. Diagram of the basic earthquake geometric parameters

The breaking and cracking of the rocks, the movement of the adjoining blocks of the earth both vertically and horizontally (Figure A-2), as well as the production of heat, are mainly responsible for the dissipation of most of the released strain energy (Eiby, 1957). The remaining, "small" part of the energy is radiated outwards in all directions in the form of seismic waves, which travel through the body of the earth. The motion of the ground felt during an earthquake occurs once these waves reach the surface of the earth.

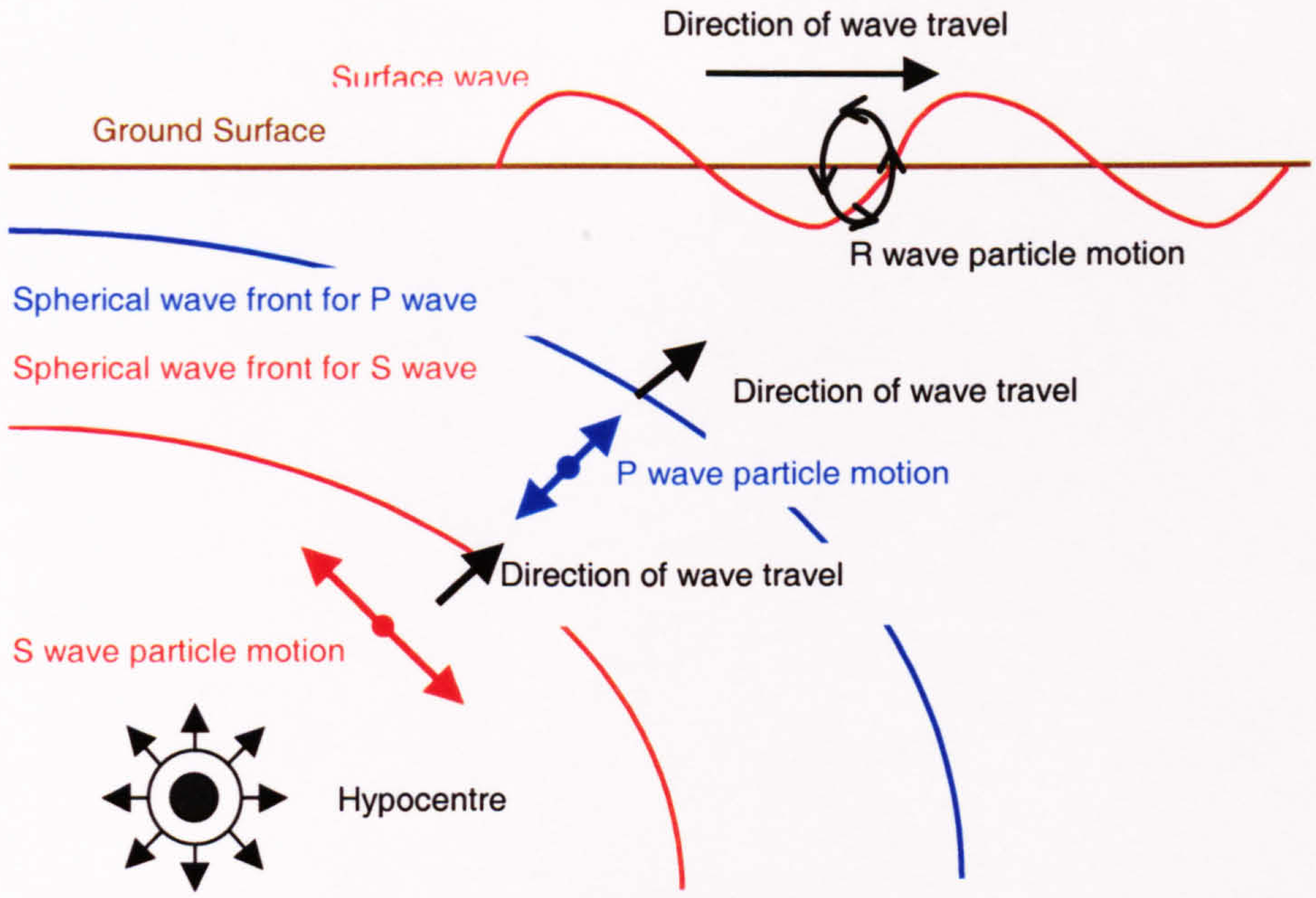


Figure A-4. Seismic waves (after Gere and Shah, 1984)

The seismic waves reach the earth's surface at various times and from more than one direction. This is mainly due to the fact that they originate along moving fracture planes rather than a single point, and they also bend and reflect as they travel within the earth. This is the reason why the recorded patterns of seismic waves are a combination of many individual waves (body waves and surface waves) (Figure A-4) (Bolt, 1978; Levy and Salvadori, 1995; Gere and Shah, 1984).

The seismic waves comprise of body waves which in turn include primary waves (P), and secondary waves (S) and surface waves which consist of Raleigh waves (R) and Love waves (L) (Bolt, 1978; Levy and Salvadori, 1995; Gere and Shah, 1984).

Body waves travel within the body of the earth, in a similar way as sound waves (Levy and Salvadori, 1995). Primary (P) waves are faster than secondary (S) waves and reach the surface of the earth first. This is illustrated in a typical seismogram included in Figure A-6 further on. The P waves are responsible for the initial agitation, whilst the S waves which usually follow in a few seconds are responsible for a distinctively sharper impact (Bolt, 1978; Levy and Salvadori, 1995; Gere and Shah, 1984).

The surface waves travel along the ground surface, matching in a way the movement of the ocean waves. They also travel at a slower speed and have longer periods (i.e. lower frequencies) than the body waves. Some of the damaging ground motion in earthquakes comes from these waves. The Raleigh (R) waves as well as the Love (L) waves behave in a similar way to water waves and move continuously forward (Bolt, 1978; Levy and Salvadori, 1995; Gere and Shah, 1984).

The motion that people feel during an earthquake is the net result of various different kinds of waves. The measurement of the ground motion is achieved by the use of seismographs (see section 1.1.1.2) and those measurements are used for the determination of the magnitudes and various other characteristics of earthquakes.

Various factors must be present in order for an earthquake to occur. Initially a mechanism is required to supply the energy and stress the material. As stated earlier, for global purposes, the movement of the tectonic plates provide this mechanism. Furthermore, brittle materials must be present which they should also be able to store significant amounts of energy. That is the reason why earthquakes can not usually be produced at great depths where, due to the high temperatures and pressures, the materials become ductile and absorb rather than store the energy due to strain (Richter, 1958; Dowrick, 1987).

However, when two tectonic plates collide, eventually one subducts the other, as shown in Figure A-2. If the rate of subduction of brittle materials is high enough then the subducted material remains brittle, and deep earthquakes (depth greater than 180km) can occur.

1.1.1 QUANTIFICATION OF EARTHQUAKES

1.1.1.1 INTENSITY

Prior to the invention of instruments capable of giving a quantitative measure of earthquake magnitude, each individual event was classified according to its intensity. The intensity is the qualitative assessment of people present at the event and the observed or reported material damage (Levy and Salvadori, 1995).

The first historic records of this form were found in China and they are dated around the Ming Dynasty (1368-1644) (Levy and Salvadori, 1995). The first earthquake catalogue dating from 780 BC, was also found in China. In 1783 in Italy, Pignataro proposed a scale describing five earthquake intensities (Levy and Salvadori, 1995).

Robert Mallet was the first to make a scientific, observational field study of the aftermath of the 16th of December 1857 earthquake in southern Italy (Bolt, 1978).

Mallet collected felt reports (i.e. reports on how the event was felt) and, by combining these with observations of structural damage as well as any changes to the Earth's surface, he produced detailed maps, in an attempt to measure the strength and distribution of the ground motion.

At the same period the idea that it was possible to represent the distribution of damage caused by earthquakes by drawing lines on a map between places of equal apparent damage or of equal intensity of shaking (isoseismal lines) was becoming generally accepted (Richter, 1958). The use of the isoseismal lines enables the determination of the centre of the earthquake shaking and, therefore, the identification of the source of the seismic waves. Furthermore, according to the patterns of these lines an indication of the rate at which the shaking effects diminished with distance could be established. This provided an estimate of the relative size of the earthquake.

Earthquake intensity has since been used widely as a mean of estimating the size (damaging effect) of an earthquake. The intensity of an earthquake is defined as the observed effects of ground shaking on people, buildings and the ground surface at a specific location in the focus area.

When scientists first started to study earthquakes each earthquake event was examined and investigated individually (Richter, 1958). This was possible due to the limited number of reported earthquakes. The comparison of specific earthquake investigations led to a common pattern that suggested the need for intensity scales intended for general application. These general application intensity scales were developed gradually. In the 1880s De Rossi and Forel developed the first intensity scale. The Rossi-Forel scale is a ten-degree scale and is indicated by the abbreviation R.F. followed by a Roman numeral according to the degree of the event from I to X. The Rossi-Forel scale is still sometimes used to describe earthquake intensity (Levy and Salvadori, 1995).

In 1902 Mercalli proposed an improved ten-degree scale with more detailed and clear definitions, and in 1931 the twelve-degree Modified Mercalli scale was introduced. This scale was widely adopted in the English speaking world. The Modified Mercalli scale is indicated by the abbreviation M.M. followed by a Roman numeral according to the degree of the event from I (felt only by few people) to XII (total damage). Alternative intensity scales like the Japan Meteorological Agency (JMA) scale, the Russian MSK scale (named after the seismologists S.V. Medvedev, W. Sponheuer and

V. Karnik) and the Chinese Intensity scale have been developed and are currently in use in their respective countries (Gere and Shah, 1984).

The subjectivity of the observer makes the application of intensity scales imperfect (Levy and Salvadori, 1995). The Intensity scale is not an accurate quantitative measurement of the effects of an earthquake.

1.1.1.2 SEISMOGRAPH

There is normally some historical evidence for past earthquakes, especially the larger events. Historical records of earthquakes before the middle of the 18th century, when instruments were introduced for seismic measurements are generally lacking or they are unreliable.

At great distances from their origin, even the most vigorous earthquakes can be detected only by means of a seismograph. The seismograph is based essentially on the law of inertia, according to which any body at rest tends to preserve its state of rest. There are many different systems of seismographs, one of them is represented schematically in Figure A-5.

Two such instruments installed at right angles to each other give us complete information about the horizontal displacements produced by the earthquake. There are of course, other seismographs designed to register the vertical jerks of the ground and the sudden changes of inclination to a fixed direction in space.

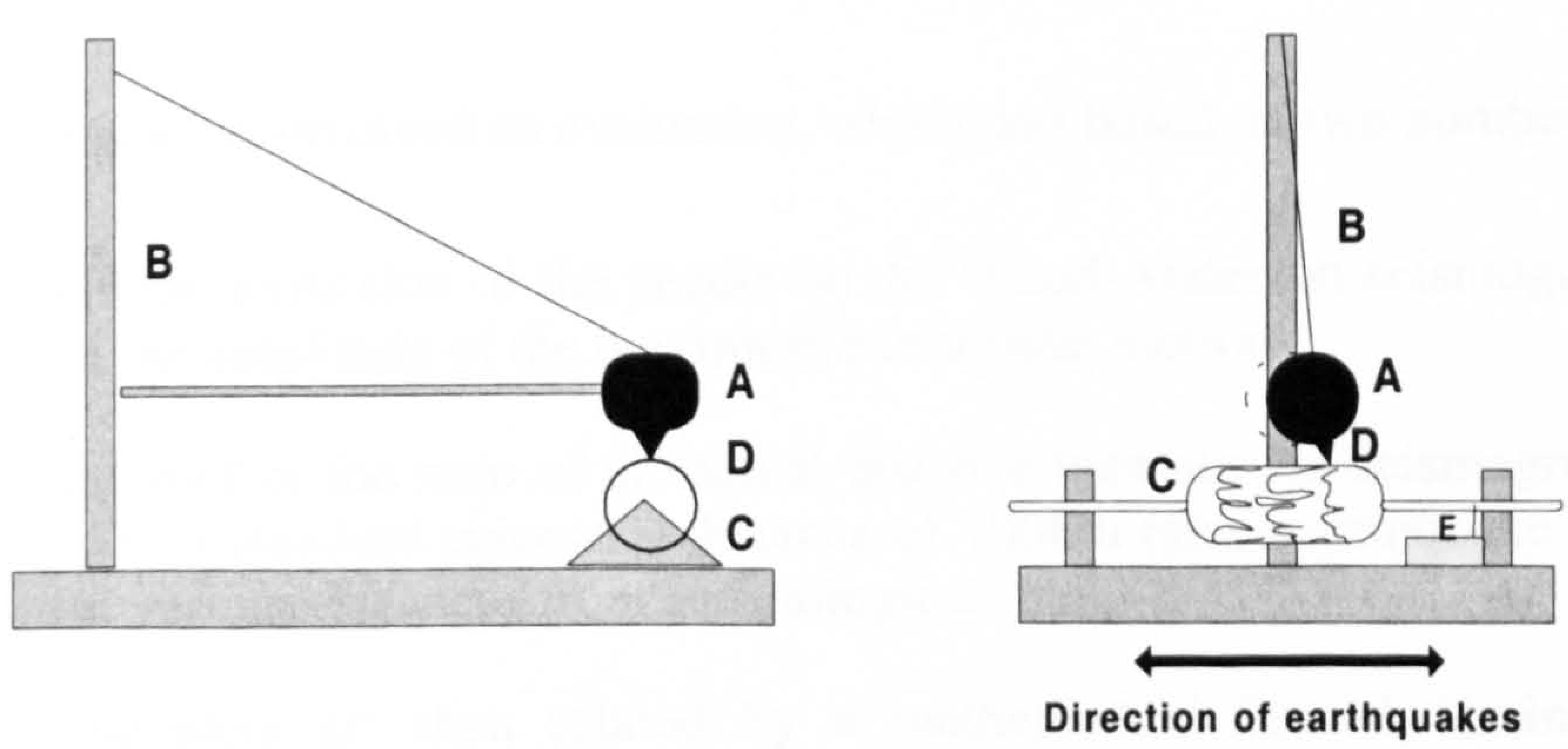


Figure A-5. Diagram of a simple seismograph. A: a heavy weight suspended from a vertical pole. B,C: a rotating cylinder driven by a clock mechanism E; D: a writing pen. The arrow indicates the direction of earthquake that can be registered by this apparatus (Gamow, 1941)

1.1.1.3 MAGNITUDE

The development of a quantitative scale that could be applied to earthquakes wherever they occur (i.e. inhabited and uninhabited regions) was essential. This became possible once the appropriate instruments were available (i.e. seismographs), which enabled the measurement of the ground movement. Wadati (1956) was the first to come up with a very simple basic idea, which he used to compare Japanese Earthquakes (Richter, 1958).

In 1935 Charles Richter (Richter, 1958; Dowrick, 1987; Levy and Salvadori, 1995) proposed the first scale for earthquake magnitude (local magnitude scale M_L). Richter's initial aim was to develop a magnitude scale to enable the standardisation of the measurement of earthquakes in southern California as recorded on a specific device, the Wood-Anderson seismograph, or its equivalent.

A logarithmic scale was chosen in order to compress the range of wave amplitudes measured on seismograms. This was required because the size of earthquakes varies immensely, and therefore the amplitudes of the waves differ by factors of thousands from earthquake to earthquake. Richter used a conventional logarithmic scale to the base of 10. He defined the magnitude of a local earthquake as: "*the logarithm to base 10 of the maximum seismic wave amplitude (in thousands of a millimetre) recorded on a standard seismograph at a distance of 100 kilometres*" from the earthquake epicentre. Therefore, a unit change in the Richter scale represents a tenfold increase in the amplitude of the earthquake waves.

Richter's suggestion involved an evaluation, which was based on two numbers:

(a) The maximum excursion of the needle on the Wood-Anderson seismograph, which measures the amplitude of the maximum earthquake motion.

(b) The square root of the ratio of the actual distance between the seismograph and the epicentre to a standard epicentral distance of 100km (since earthquake sources are located at various distances from seismological stations).

These two numbers are then related by a mathematical formula (using common logarithms $\log_{10}$) to an index M_L, now called the Richter magnitude. The diagram for calculating M_L can be seen in Figure A-6.

The second number (b) required for the evaluation of the M_L involves corrections for the conversion of the measurements obtained at distances other than 100 kilometres (since Richter's suggestion specified the distance from the epicentre to be 100 kilometres). Gere and Shah (1984) claimed that these corrections are not precise and they suggest that this is one of the main reasons for the differences in Richter magnitude announced for the same earthquake event by various seismographic stations.

Mathematically the local magnitude M_L is defined as:

$$M_L = \log A - \log A_o \qquad \textbf{(A-1)}$$

where: A is the maximum-recorded trace amplitude for a given earthquake at a given distance as written by a Wood-Anderson instrument.

A_o is that for a particular earthquake selected as standard.

The local magnitude scale, M_L had its limitations, mainly due to the fact that it was designed to measure earthquakes only in Southern California. Richter and Gutenberg recognised the limitations and they decided to develop two other scales: the body-wave scale, m_b, to accommodate deep-focus earthquakes (focal depth > 45km), and the surface-wave scale, M_S, for measuring more distant and larger earthquakes.

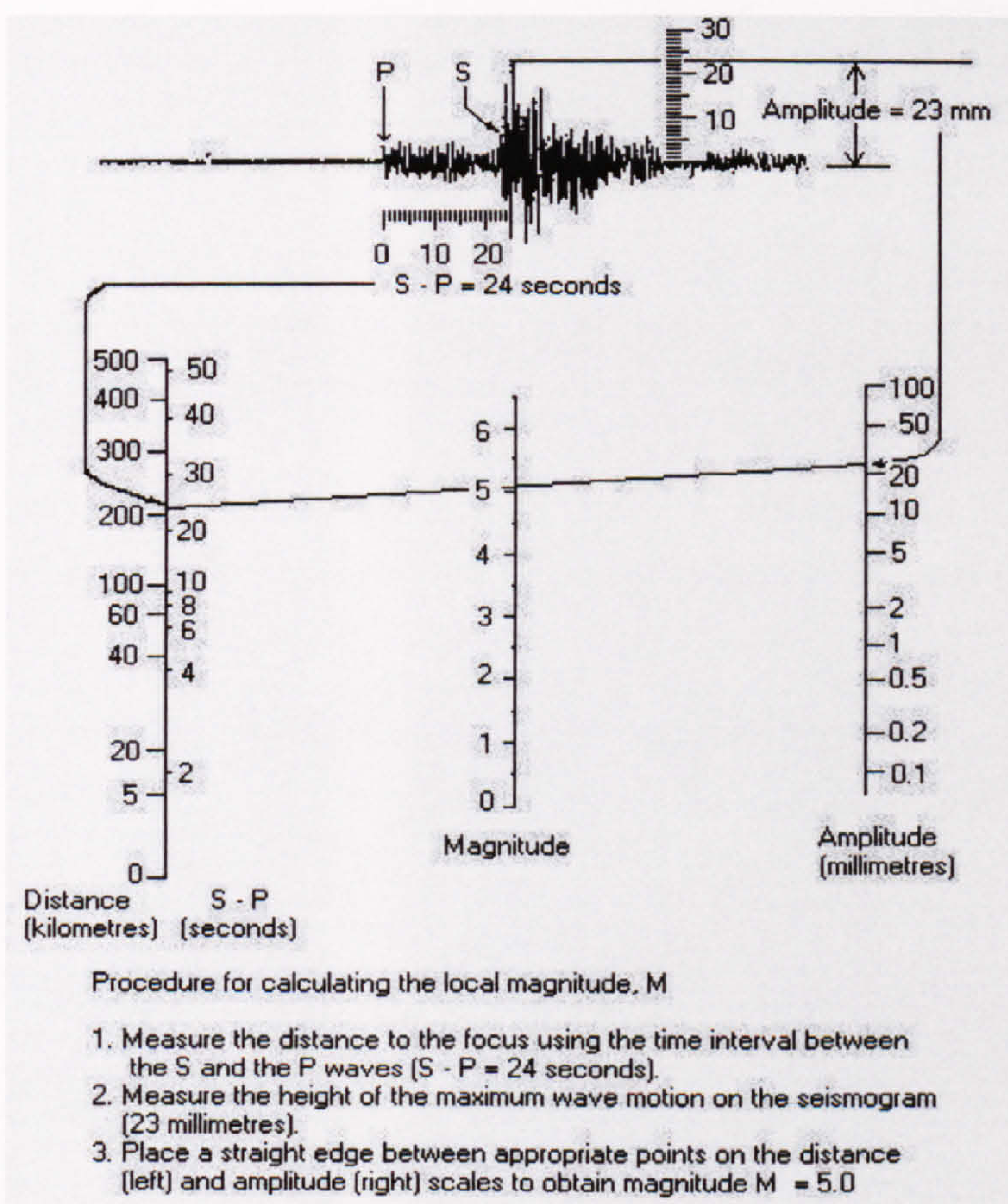


Figure A-6. Chart for determining Richter Magnitude (M_L) of a local earthquake. This chart is for a particular seismographic station, each station uses a different chart (Bolt, 1978)

Two relationships are given by Richter (1958) for the m_b and M_S:

$$m_b = 2.5 + 0.63 M_S \quad \text{(A-2)}$$
$$M_S = 1.59 m_b - 3.97 \quad \text{(A-3)}$$

where: m_b is the body-wave magnitude.
M_S is the surface-wave magnitude.

As far as Dowrick (1987) is concerned the body-wave magnitude (m_b) was the result of Gutenberg's proposal for a "unified magnitude" which would be dependent on body waves. Gutenberg believed this to be necessary since the surface-wave magnitudes (M_S) were not always reliable.

Table A-1, suggests that the different magnitude scales do not result in consistent values. Since there is a continuous inconsistency (Table A-1) between values of magnitude determined by the above methods it is important to know the type of magnitude being used.

Table A-1. Magnitudes for some Californian earthquakes (Dowrick, 1987)

Event	$M_o \times 10^{25}$ (dyn. cm)	M_L	M_S	M_m	m_b
San Francisco, 18 April 1906	400		8.25	7.7	7.7
Long Beach, 10 March 1933	2	6.3	6.25	6.2	6.4
El Centro, 18 May 1940	30	6.4	6.7	7.0	6.7
Kern County, 21 July 1952	200	7.2	7.7	7.5	7.3
San Francisco, 9 February 1971	20	6.4	6.6	6.6	6.6
Point Mugu, 21 February 1973	0.1	5.9	5.2	5.3	5.7

Dowrick (1987) suggests that the moment magnitude (M_m) developed by Hanks and Kanamori in 1979 has more potential. This scale is defined as:

$$M_m = \tfrac{2}{3}\log M_o - 10.7 \quad \text{(A-4)}$$

Another quantity, known as seismic moment (M_o) has also been introduced recently in an attempt to overcome the difficulties in obtaining a meaningful magnitude number by measuring the wave amplitude on a seismogram (Gere and Shah, 1984). The seismic moment though is used primarily in research.

The existence of all these different scales inevitably results in confusion created when Richter magnitudes of recent earthquake events are announced by the news media.

Nowadays, the term magnitude conveniently describes the size of an earthquake. In order though for the term to be globally adopted, the method first suggested by Richter had to be extended to apply to a number of types of seismographs all over the world. As a result a variety of magnitude scales, based on different formulas for epicentral distance and ways of choosing an appropriate wave amplitude, have emerged.

Throughout the world and especially at the areas of regular seismic activity research centres or stations have been developed to examine the earthquake events, analyse them and also do research concerning their prediction.

Each seismographic station has its own correction formulas that it uses for this purpose. The variables taken into consideration by these formulas are:

a) Distance to the epicentre (epicentral distance) (Figure A-3)
b) Direction of the epicentre
c) Focal depth
d) Local geological conditions

The existence of various seismic stations at different locations throughout the world helps to cross correlate their individual measurements of an event and therefore, to analyse it better. The World Wide Standard Seismograph Network (WWWSSN) incorporates some 125 stations throughout the world.

The first Seismological station in the island of Cyprus was established in 1984. During the 15 years period the station is in operation it recorded mainly small local events with only a few big ones (1995, 1996, 1997, 1999) stirring the general tranquillity. The Cyprus seismic network, its situation and procedures are examined in more detail in chapter 2.

1.1.1.4 Relationship Between Richter Magnitude and Mercalli Intensity

As stated above, the intensity and the magnitude of an earthquake are measured on two different scales. Whilst the first is measured on the Mercalli scale and is based on observations, the second is measured on the Richter scale and is based on the output of seismographs. Magnitude and Intensity scales measure different aspects of the strength of an earthquake.

Generally the highest intensity depends on the magnitude. The higher the energy released during an earthquake event, the more the resulting damage of that event. However, this is not always true.

Depending on where an earthquake occurs (i.e. inhabited or uninhabited area) it might have a high magnitude and a low intensity, or vice versa (Levy and Salvadori, 1995). If, for example, a high magnitude earthquake occurs in the middle of a dessert it is obvious that any damage to structures would be almost non-existent. On the other hand, if a low magnitude earthquake occurs in or near a large city it could easily cause considerable structural damage, injury or even death to the city's inhabitants.

The Magnitude is not the only quantity that affects the intensity of an earthquake. The general hydrogeology of the area, as well as the vulnerability of the structures situated in that area can also affect the intensity (see section 1.1.2).

It can be therefore concluded that each scale has its purpose. If the cases described above are taken into consideration it can be said that while on the first case (i.e. uninhabited area) the earthquake would be characterised better by the magnitude scale, on the second case (i.e. inhabited area) it would be better defined by the intensity scale (Levy and Salvadori, 1995). This is justified since for the intensity scale to work observations are needed. In the first case there is unavailability of observations since the area is uninhabited, whilst on the second case the collection of massive amounts of felt reports would be expected.

In general every earthquake has only one Richter magnitude, but it may generate many intensities varying from a high intensity in the most heavily damaged region down to the lowest intensity (no damage) far from the epicentre. Hence, a more absolute measure of an earthquake may be a measure of the seismic energy released.

1.1.1.5 SEISMIC ENERGY

Earthquakes are the result of the sudden release of the strain energy stored in the rigid layers in the earth. The energy release of an earthquake can be considered to be a measure of its size, and to a certain extend this is what is measured by the earthquake magnitude scale (Bolt, 1978). Even though the equivalence is a rough one, it is useful for calculating the approximate amount of energy actually released in earthquakes. It must be mentioned that an increase of one in the Richter scale (local magnitude M_L), does not really represent the corresponding enormous increase in the energy of an earthquake (Levy and Salvadori, 1995).

The relationship that associates the magnitude of an earthquake with the energy release was given by Richter (1958) as:

$$\log E = 11.4 + 1.5M_S \quad \textbf{(A-5)}$$

where: E is the energy factor
M_S is the surface-wave magnitude

This relation between energy release and magnitude was used to prepare Table A-2. There is a rapid rate of increase of seismic energy with increase in magnitude. An increase of one unit in the earthquake's magnitude corresponds almost to an increase of thirty-two times in the earthquake's energy E.

Gutenberg, in an attempt to relate the local magnitude M_L to the seismic energy E, he came up with two more equations (in Richter, 1958). The first related his "unified magnitude" (i.e. body wave magnitude m_b) to the local magnitude M_L (Equation A-6). This led to equation A-7, which related the local magnitude M_L to the seismic energy E.

$$m_b = 1.7 + 0.8M_L - 0.01M_L^2 \quad \textbf{(A-6)}$$
$$\log E = 9.9 + 1.9M_L - 0.024M_L^2 \quad \textbf{(A-7)}$$

Table A-2. Seismic Energy of Earthquakes based on Surface Wave Magnitude M_S and Local Wave Magnitude M_L

Magnitude M_S or M_L	Seismic Energy (ergs)		Energy Ratio for each Unit Increase in Magnitude		Energy Ratio Compared to a Magnitude 4.0 Earthquake	
	M_S	M_L	M_S	M_L	M_S	M_L
4.0	0.0025×10^{20}	0.0013×10^{20}	-	-	1	1
5.0	0.079×10^{20}	0.063×10^{20}	32	48	32	48
6.0	2.51×10^{20}	2.73×10^{20}	32	43	1000	2089
7.0	79.4×10^{20}	106×10^{20}	32	39	31623	80910
8.0	2510×10^{20}	3664×10^{20}	32	35	1000000	2805434

Gutenberg's equations were also used for the preparation of Table A-2. It is apparent that, although the numbers are different, the general pattern is similar. The tremendous rate of increase of the seismic energy is once more illustrated.

Figure A-7 was prepared in an attempt to help the visualisation of the energy comparisons. The idea was taken from Gere and Shah, 1984. To enable the better understanding of the massive amounts of energy released during an earthquake, the energy released by the Atomic Bomb, as well as the 2000 daily electrical energy consumption in the UK (as given by the Government Statistical Service), are also presented. The sloping line gives the relationship between energy and magnitude as obtained from Richter's equation, whereas Gere and Shah, (1984) used Gutenberg's equation.

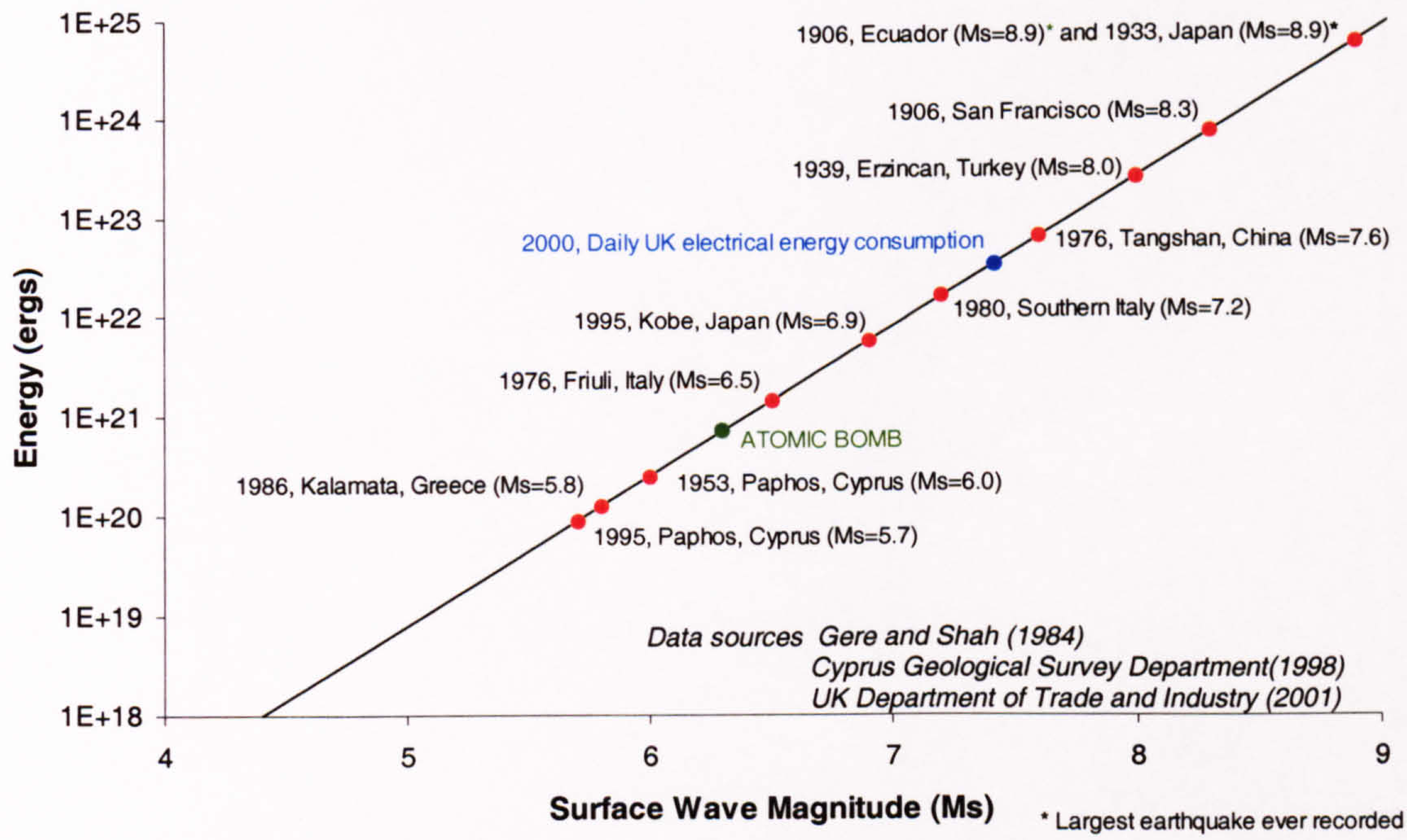


Figure A-7. Seismic Energy versus Surface Wave Magnitude (M_S)

For the purposes of this research both magnitude and seismic energy release will be used in the attempt to reanalyse and attribute in space the seismicity of Cyprus.

1.1.2 EFFECTS ON EARTHQUAKE DAMAGE

There are four main parameters that determine the level of expected damage in structures due to earthquakes and these are examined in the following.

1.1.2.1 ATTENUATION

Structural damage depends on the induced ground motion due to the seismic waves, which attenuate away from the hypocentre of the earthquake towards the focal area (Figure A-3). The term attenuation means the decrease in average intensity of shaking with distance from the earthquake source.

Attenuation is caused by the radial spreading of seismic energy with distance from a given source (termed geometrical attenuation) and by the absorption and scattering of seismic energy in different earth materials (termed anelastic attenuation).

Even though the seismic waves are measured in terms of ground accelerations their attenuation is customarily defined in terms of intensities (Figure A-8). The soil type and conditions affect the amplitude of the seismic waves and consequently the intensity attenuation pattern. To precisely assess the attenuation of intensities (or ground accelerations) in a specified region is a difficult task.

The isoseismal maps (Figure A-8) which show the distribution of the intensity of an earthquake are mostly contouring out of the epicentre as a result of attenuation.

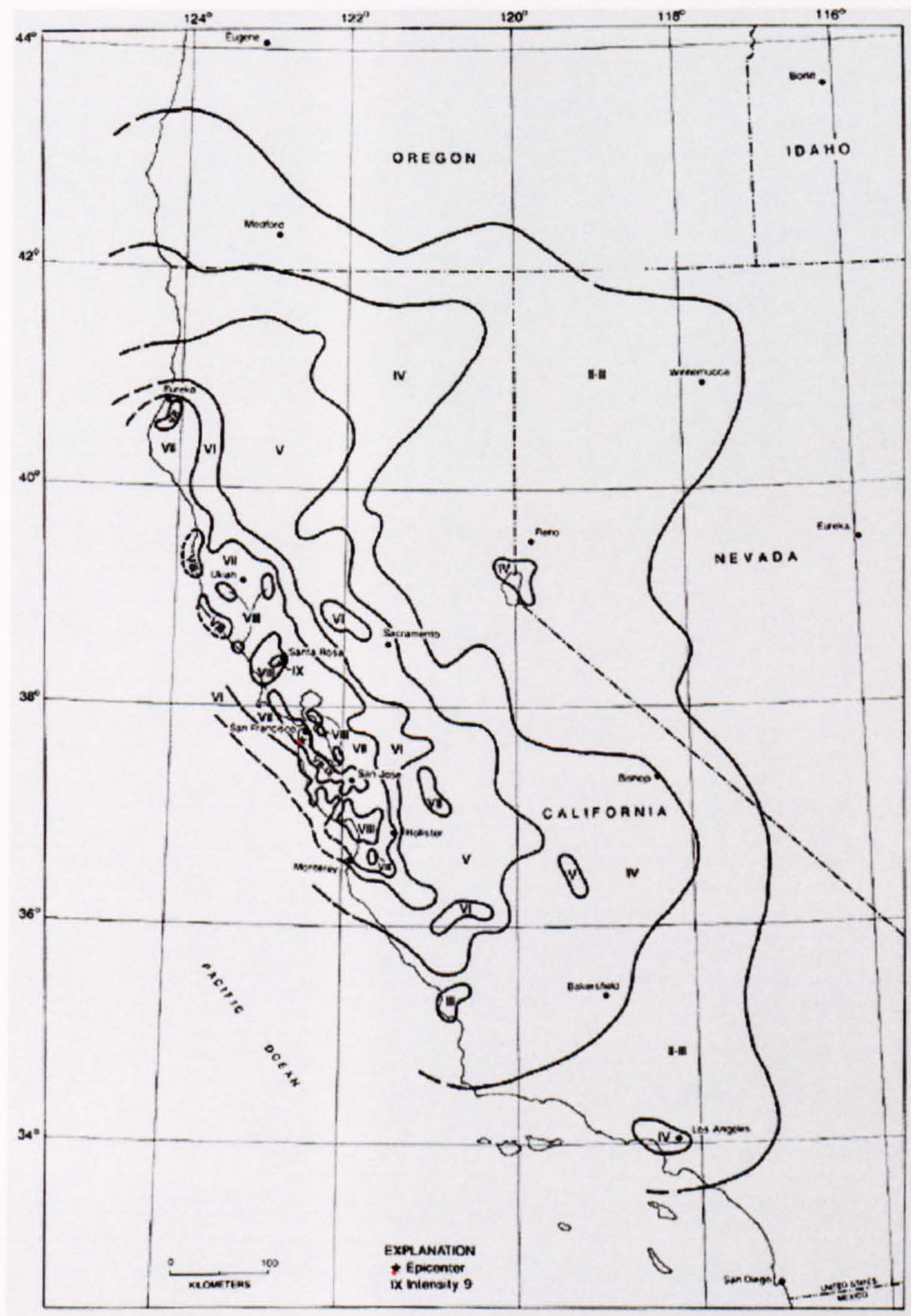


Figure A-8. Intensity Map of the 16th April 1906 San Francisco earthquake (Stover and Coffman, 1993)

The attenuation of intensities or the ground accelerations are expressed by the use of various attenuation laws, which are a function of the magnitude (M), intensity (I) or peak ground acceleration (PGA), and the epicentral distance (r) (Figure A-3). Two of these attenuation laws are presented. The first (equation A-8) is expressed in terms of intensities (Wakabayashi, 1986), and the second (equation A-9) in terms of ground accelerations (Ambraseys and Bommer, 1995).

$$I = 8.16 - 45M_S - 2.46\ln r \qquad \text{(A-8)}$$

$$Log_{10}A = -0.87 + 0.217M_S - Log_{10}\sqrt{(R^2 + r^2)} - 0.00117\sqrt{(R^2 + r^2)} \qquad \text{(A-9)}$$

where: A is the peak ground acceleration
r is the epicentral distance (Figure A-3)
R is the focus depth (Figure A-3)

Whilst the data used for the derivation of the first equation are unknown, the second equation was derived from data collected in Europe and the Middle East. For the purpose of our research the second equation seems more reliable.

1.1.2.2 EFFECT OF DEPTH

The earthquake hypocentre or focus (Figure A-3) is the point from which the seismic waves first originate. This point is always at some depth below the ground surface.

Although in many cases the focus of an earthquake could be situated at a shallow depth, in some regions (i.e. South American plate/Nazca plate) they are hundreds of kilometres deep normally associated with a deep ocean trench (Figure A-2). According to their depth earthquakes are separated in three categories (Table A-3).

Table A-3. Depths of earthquakes

h < 60km	shallow earthquake
60km <h > 300km	intermediate earthquake
h > 300km	deep earthquake
h - depth of the earthquake	

The depth (h) of an earthquake plays an important role in its destructiveness, since the shallower the centre or focus of the event the stronger its intensity. The shallow earthquakes are responsible for about 3/4 of the total energy released by earthquakes throughout the world.

Depth is of great importance since a stronger ground shaking may affect a site when the focus is at shallow depth. Unfortunately, due to the nature of seismological measurements the determination of an earthquake's depth is not as precise as the identification of the location of its epicentre on the surface of the earth.

The knowledge of the location of the earthquakes focus (i.e. depth) suggests the shape and size of the region beneath the surface that is the source of the earthquakes. This evidence may enable the identification of a tectonic structure, such as an arc, and even the estimation of its length. Nowadays seismologists are able to estimate the strength of future earthquakes with only knowledge the length of an arc.

A strange pattern emerges when the focuses of earthquakes near island arcs such as Cyprus are compared with their depths. It seems that a dipping seismic zone, which is generally known as Benioff zone, is present. This will be examined further when analysing the seismicity of Cyprus.

1.1.2.3 HYDROGEOLOGY

The geology of an area controls the ground cracking, subsidence, landslides and thereby the distribution of damage to structures. In general the stronger the ground upon which a structure is placed, the lesser the extent of the damage it will suffer during an earthquake. Unconsolidated deposits such as alluvium, talus and clays are not desirable, as they amplify the induced ground motion, resulting in greater damage on buildings.

The amplification of seismic waves will vary in different parts of an area depending on the soil type and condition. As the seismic waves pass from the more rigid basement rocks to soils like weathered surface rocks, alluvium and saturated (water filled) soils they might be increased or decreased.

An example of how local soil conditions can greatly influence local intensity is given by the catastrophic damage in Mexico City from the 1985, M_S 8.1 Mexico earthquake (Bolt, 1999). Even though the epicentre of the earthquake was 350 km away from Mexico City, the shaking of loose sediments in the capital was much stronger than at the epicentre. Resonance of the soil-filled basin under parts of Mexico City amplified ground motions for periods of 2 seconds by a factor of 75 times. This shaking led to selective damage to buildings 15 - 25 stories high (same resonant period). Nearly 10,000 people died and central Mexico City was heavily damaged (Bolt, 1999). Liquefaction of the lakebed sediments was a critical factor.

According to Richter (1958) even though it is generally accepted that sedimentary and alluvial cover affect the intensity, this is not taken into account when preparing the isoseismal maps. Hence, a good presentation of the detailed effect of ground in modifying the intensity is essential. This will enable the use of the isoseismal map as an index to danger spots, which could be avoided in future construction or in cases of existing structures the appropriate safety measures can be taken.

1.1.2.4 VULNERABILITY

Vulnerability is the amount of damage, caused by a given degree of hazard and expressed as a fraction of the value of the damaged item under consideration.

The vulnerability of man-made structures depends on various parameters. Primarily the age and the height of the element at risk (building, dam, road etc.) and secondly the quality of the materials used for its construction.

Ambraseys and Jackson (in Dowrick, 1987) developed relationships for the total damage to houses as functions of epicentral intensity and of magnitude. For the purposes of their research they separated the types of construction into six groups.

Figure A-9 shows the percentage of houses destroyed or made uninhabitable for MMI greater than VI as a function of magnitude, for a population density of 50 per km^2. The different coloured curves represent different construction types. The percent of total loss of non-engineered construction types (R and A) is much higher than the one for the construction types with basic engineering content (B, T, S, s). This result can be used as a representative measure of their vulnerability.

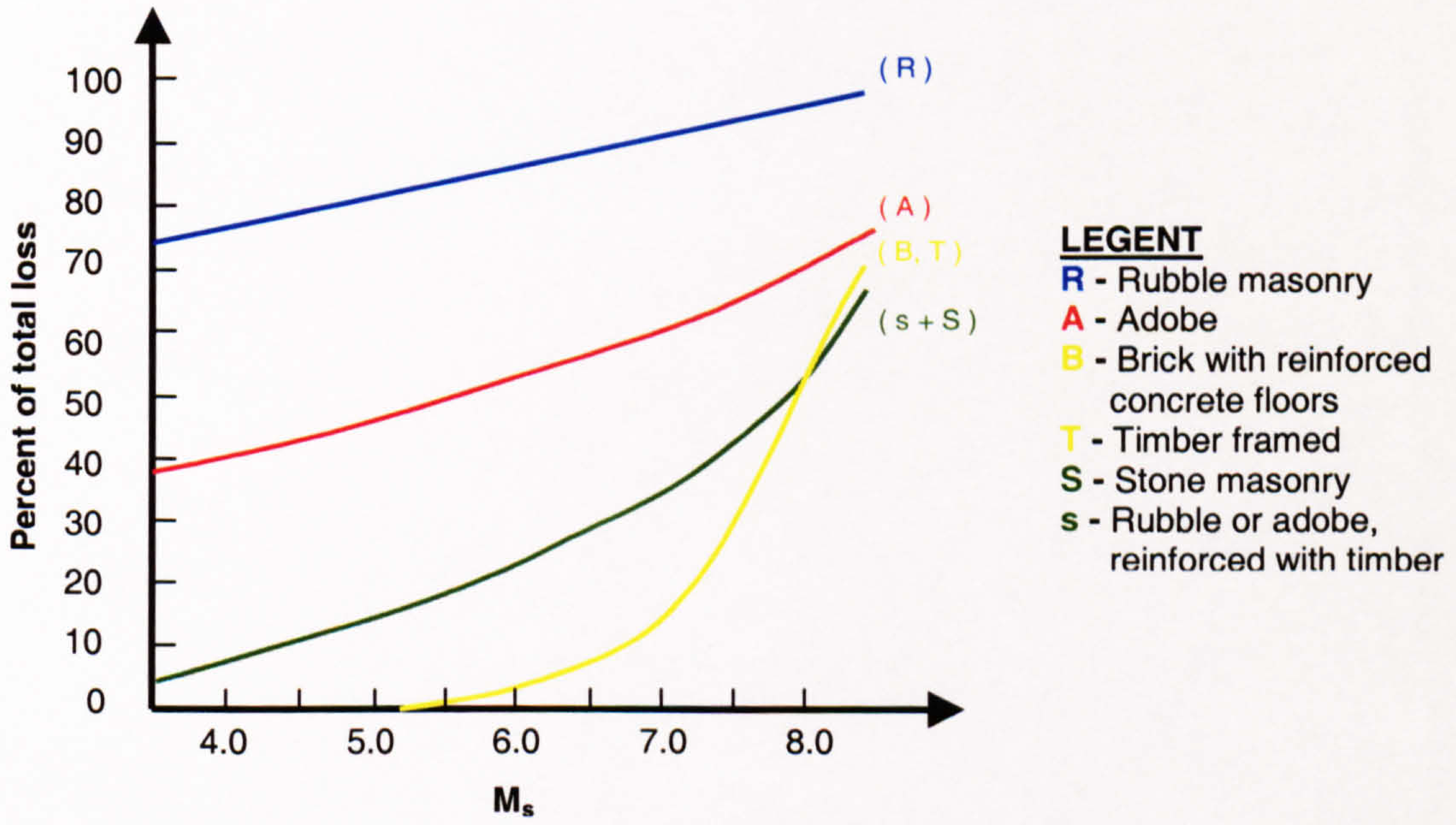


Figure A-9. Vulnerability of houses for Greece and Turkey region (Ambraseys and Jackson, 1981 in Dowrick, 1987)

1.2 EARTHQUAKE HAZARDS AND THEIR EFFECTS

The hazards associated with earthquakes, and their effects need to be understood and quantified.

Earthquake effects may be classified as primary and secondary (Richter, 1958). The primary effects are mainly caused due to the faulting or volcanic action. The secondary, are the result of the shaking. The shaking by itself occurs due to the passage of the elastic waves (i.e. seismic waves) generated by the primary process (i.e. faulting or volcanic action). The earthquakes that affect the area of Cyprus occur due to faulting. These kinds of earthquakes are called tectonic. Table A-4 presents only the primary effects that could be produced by tectonic earthquakes. In the case of a volcanic earthquake the resulting primary effects could be entirely different.

Table A-4. Principal Macroseismic Effects of tectonic Earthquakes (Richter, 1958)

Effects on	Primary	Secondary Permanent	Secondary Transient
Terrain	Regional warping, etc Scarps Offsets Fissures, mole tracks, other trace phenomena Elevation or depression of costs; changes in coast line	Landslides (slumps, flows, avalanches, lurches)[1,2,3] Secondary fissures[3] Sand craters[4] Raising of posts and piles	Visible waves Perceptible shaking
Water (ground and surface)	Damming; waterfalls; diversion Sag ponds Changes in wells, springs		Changes in well levels Earthquake fountains[4] Water over stream banks Seiches Tsunamis Seaquakes
Works of construction	Offsets, and destruction or damage by rending or crushing; buildings, bridges, pipe lines, railways, fences, roads, ditches	Most ordinary damage to buildings, chimneys, windows, plaster	Creaking of frame Swaying of bridges and tall structures
Loose objects		Displacement (including apparent rotation) Overturning, fall, projection (horizontal or vertical)	Rocking Swinging Shaking Rattling
Miscellaneous		Clocks stop, change rate, etc. Glaciers affected Fishes killed Cable breaks	Nausea Fright, panic Sleepers wakened Animals disturbed Birds disturbed Trees shaken Bells rung Automobiles, standing or in motion, disturbed Audible sound Flashes of light

[1] Earth flows properly belong with water phenomena.
[2] Landslides may produce damage to works of construction.
[3] Landslides and secondary fissures may produce the effects on terrain and on surface water listed as primary.
[4] Production of sand craters and fountains is a single phenomenon.

The secondary effects of an earthquake can be separated into the permanent and transient (Table A-4). The permanent, are basically the remains of an earthquake (i.e. damaged buildings) while the transient (i.e. rocking, swinging etc) are the ones felt or seen during the event.

The potential phenomena generated by an earthquake are summarised in (Table A-4). Some of these natural hazards will be presented in more detail below. In addition to that a number of man-made hazards will also be discussed.

1.2.1 GROUND SHAKING

Ground shaking is the primary cause of earthquake damage to man-made structures. During an earthquake the surface of the earth undergoes an unexpected and more or less violent shaking. At its mildest it may be taken for the passing of a truck, or for a gust of wind. However, if the ground shakes strongly, buildings, roads and bridges can be damaged or completely destroyed and hillsides (landslides) can be moved (Eiby, 1957). Ground shaking is normally quantified in terms of acceleration at a particular location. The dynamic characteristics of the ground shaking are taken into account in design of structures through the response spectrum.

1.2.2 AFTERSHOCKS

A significant earthquake is always followed by aftershocks. The greater the magnitude of the main shock the larger the number and magnitude of the aftershocks. This also applies to the duration of the aftershock activity.

Usually the strength of the magnitude of the foreshocks and aftershocks can not be compared to the one of the main shock. This has given a false reassurance to the general public that once a big earthquake hits an area, the thread of the serious danger is over. Unfortunately this is not a scientifically sound procedure, since a strong damaging shock could very easily be the foreshock of an even greater earthquake. Furthermore, it is not impossible for aftershocks to be as strong as the main event or strong enough as to create further damage. A widespread pattern of the epicentres of the aftershocks is always probable.

1.2.3 LIQUEFACTION

Liquefaction is a process in which cohesionless soils (usually sand), due to high ground water level (i.e. soil will be saturated), vibration at specific frequencies and sufficient time of shaking (i.e. usually 10–20 seconds), change from firm materials into viscous semi-liquid materials that resemble quicksand (Gere and Shah, 1984). According to the area of occurrence (plain or inclined), liquefaction will either simply swallow the structures, trees etc. or trigger a landslide. This occurs because the soil liquefies and begins to flow and it can not therefore support the weight of any soil or structure above it.

In the case of Cyprus liquefaction is likely to occur in the coastal regions. Liquefaction was reported during the 1953 Paphos earthquake. Hence, the hydrogeology of Cyprus will need to be studied.

1.2.4 LANDSLIDES

Landslides can also be triggered without the occurrence of liquefaction. Earthquakes have triggered great landslides in the past and they could trigger even more in the future. The risk of great landslides though can be foreseen and consequently avoided, since the conditions, which give rise to such catastrophes, are not realised suddenly at the time of the earthquake.

Landslides lead to the destruction of several villages of the Paphos district in 1953. Again this hazard will need to be assessed when dealing with Cyprus.

1.2.5 SURFACE FAULT RUPTURE (FISSURES)

The fear that the earth might split in two during an earthquake and consequently swallow the ground was present since the beginning of time. Surface fault rupture (i.e. the opening of fissures) is either an effect in the zone of a great fault or an outcome of shaking and ground water disturbance in heavily alluviated areas. Fortunately the risk to life is small (Richter, 1958) on the other hand the damage to property might be from minor to extensive.

Surface faulting due to recent earthquakes only poses a problem to dams in Cyprus and will not be a subject of further investigation.

1.2.6 TIDAL WAVES (TSUNAMIS)

The islands of Japan have suffered tremendous disasters from the destructive effects of sea waves produced by earthquakes, and in some cases these waves travelled from as far as South America. The Japanese call these waves tsunamis, and their word has been internationally accepted and adopted.

Tsunamis are the result of sudden offsets of major faults under the ocean floor, which move the water in a way as if a great paddle was pushing it (Bolt, 1978). This movement produces long water waves at the ocean surface, which in time spread out from the proximity of the earthquake source and move across the ocean until they reach a coastline. However, a number of cases where the epicentre of the shock was definitely some distance inland was established by Gutenberg (in Eiby, 1957). Therefore, it could be possible for tsunamis to start either by changes on the sea bottom, such as faulting or slumping, or by some effect of the seismic surface waves passing across the shallow continental shelf.

It is quite possible for their height to increase significantly before they crash down upon the shore with disastrous effects. There have been cases were their impact was so tremendous that whole towns have been wiped out. In 1500 BC the volcano in the island of Santorini erupted. This generated a tsunami, which hit the island of Crete resulting in the total devastation of the north coast of the island. This is believed to be one of the reasons for the sudden eclipse of the Minoan civilisation (Bolt, 1978).

Other names given to tsunamis are tidal waves, even though they have nothing to do with the tides and more appropriately seismic sea waves. In South America they are known as maremoto. Recently, a huge tsunami triggered by a magnitude 7.0 earthquake hit Papua New Guinea killing more than one thousand people.

The risk of tidal waves in Cyprus is documented in the history and this will need to be further examined.

1.2.7 SEICHE

Forel (of the Rossi-Forel intensity scale) first studied seiches in 1890. The word Seiche comes from Switzerland. A Seiche is a stationary wave set up on the surface of an enclosed body of water such as a lake, pond, dam or tank (Richter, 1958). The water oscillates, bubbling back and forth (Figure A-10). So in general one could suggest that seiche is to a lake, dam or tank what tsunami is to an ocean or sea.

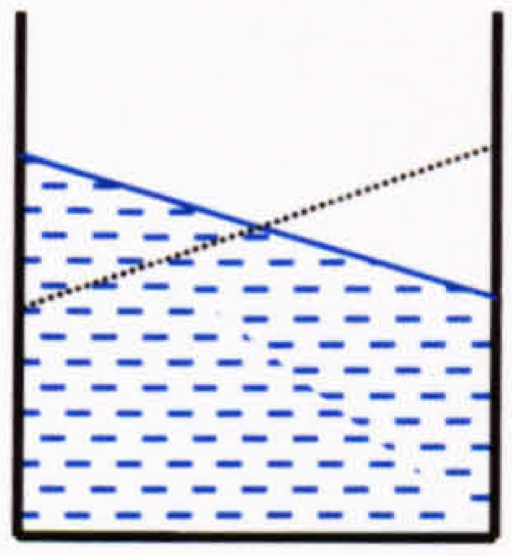


Figure A-10. Schematic section of seiche in a tank (Richter, 1958)

Seiches are therefore responsible for water being splashed out over the banks of the specific water enclosure (i.e. lake, river, pond, etc.).

Cyprus has no significant natural water enclosures and hence seiches are not considered to be of a problem.

1.2.8 FIRE

In general the long-term risk of fire is usually considered to be greater than that of earthquakes. Fire is one of the main consequences of earthquakes. Some of the initiators of fire after an earthquake are tank failures, gas pipeline breaks, electrical cable tears etc. An example of the tremendous power of fire after an earthquake is the earthquake of San Francisco in 1906. The earthquake was by it self quite destructive but the disaster, which was caused by the fire that, followed was even worse.

Due to the nature of construction in Cyprus, fire after earthquakes tend to stay localised and hence no further assessment of this hazard is required.

1.2.9 RELEASE OF TOXIC MATERIAL

This hazard might occur in cases of structural damage to nuclear reactors or chemical factories, which is possible to trigger radioactive leaks. In addition to that toxic materials can also be released due to the burning of certain materials.

Even though only small activity exists in Cyprus regarding the chemical industry, recent accidents highlight the need for a small-scale assessment of this risk.

2 GEOGRAPHICAL INFORMATION SYSTEMS

2.1 INTRODUCTION

A Geographical Information System (GIS) can be considered as the computerised equivalent of the map.

Whilst maps have been in existence since people started travelling, their traditional stationary form has not been significantly altered, even though it is characterised by various drawbacks, a number of which are listed below:

- Since they are made out of stationary material it is difficult and expensive to keep up to date.
- The fact that they are made out of stationary means that they lose flexibility. A map on a piece of paper does not allow you to zoom in and obtain further and more detailed information.
- Having one map, which displays a lot of information, makes the task of extracting the required data very difficult.

However, a GIS allows the extraction of different sets of information from a single map (roads, settlements, vegetation, etc.). This is feasible since different input data are displayed on different layers.

GISs have three very particular characteristics, which make them essential for any modelling and analysis, which need spatial considerations. The capability of the GIS for spatial analysis favours the handling of regional information. A GIS is a computer system able to assemble, store, manipulate, and display geographically referenced information (data identified according to their location).

2.2 GIS - SEISMIC HAZARD AND SEISMIC RISK

Seismic hazard and risk analyses can play a major role in identifying the potential consequences of an earthquake. In order to make such analyses large databases of geological and geotechnical information, are required. Geographical Information Systems provide an environment suitable for managing, analysing and presenting vast amounts of data, fulfilling therefore the needs of seismic hazard and risk analyses (King and Kiremidjian, 1993). The ability of a GIS framework to store data, which can be easily updated ensures that the hazard analyses will not loose their usefulness with time (Frost and Chameau, 1993).

There are numerous advantages arising from the use of a GIS in seismic hazard and risk analyses. Firstly a GIS can combine the effects of various factors required to describe the geological and geotechnical hazards, such as the geology and hydrology of the area under consideration, in performing the analyses. Secondly it provides an information management system which has the flexibility to be updated to reflect changes in analytical procedures and the availability of additional data as technology advances. Thirdly due to its superior data handling and analytical capabilities, a GIS provides an environment suitable for implementing existing analytical procedures as well as developing new evaluation procedures (Frost and Chameau, 1993).

Various researchers (Noller et al., 1991; Rhea et al. 1991; King and Kiremidjian, 1993; Faust, 1993) have implemented the use of GIS to enable them to estimate the seismic hazard and as a result the seismic risk of a particular area.

The methodology for the development of a GIS framework for a regional seismic hazard and risk analysis suggested by King and Kiremidjian (1993), combines the following aspects:

1) automated mapping systems for input and output information,
2) database management systems for storing and relating the spatially-referenced data,
3) analysis and modelling systems for manipulating and synthesising the data.

In order to get to the last stage of the risk assessment (i.e. regional damage and loss distribution), the seismic hazard of the area under consideration must be established and combined with information regarding the infrastructure. King and Kiremidjian suggest the association of the seismic hazard with direct ground shaking as well as with other secondary effects such as liquefaction, landslides and fault rupture.

Figure A-11 shows how the various types of information, required for an extensive regional seismic hazard and risk analysis, to be combined in the GIS. Each one of the maps involved contains a large quantity of spatially referenced information. The manipulation and combination of the data given by each map will consequently produce misrozonation maps. The resulting microzonation maps (i.e. damage distribution and loss estimation) will be used by planners, managers, and other decision-makers involved in hazard and risk mitigation programmes to get information regarding the seismic hazard and risk.

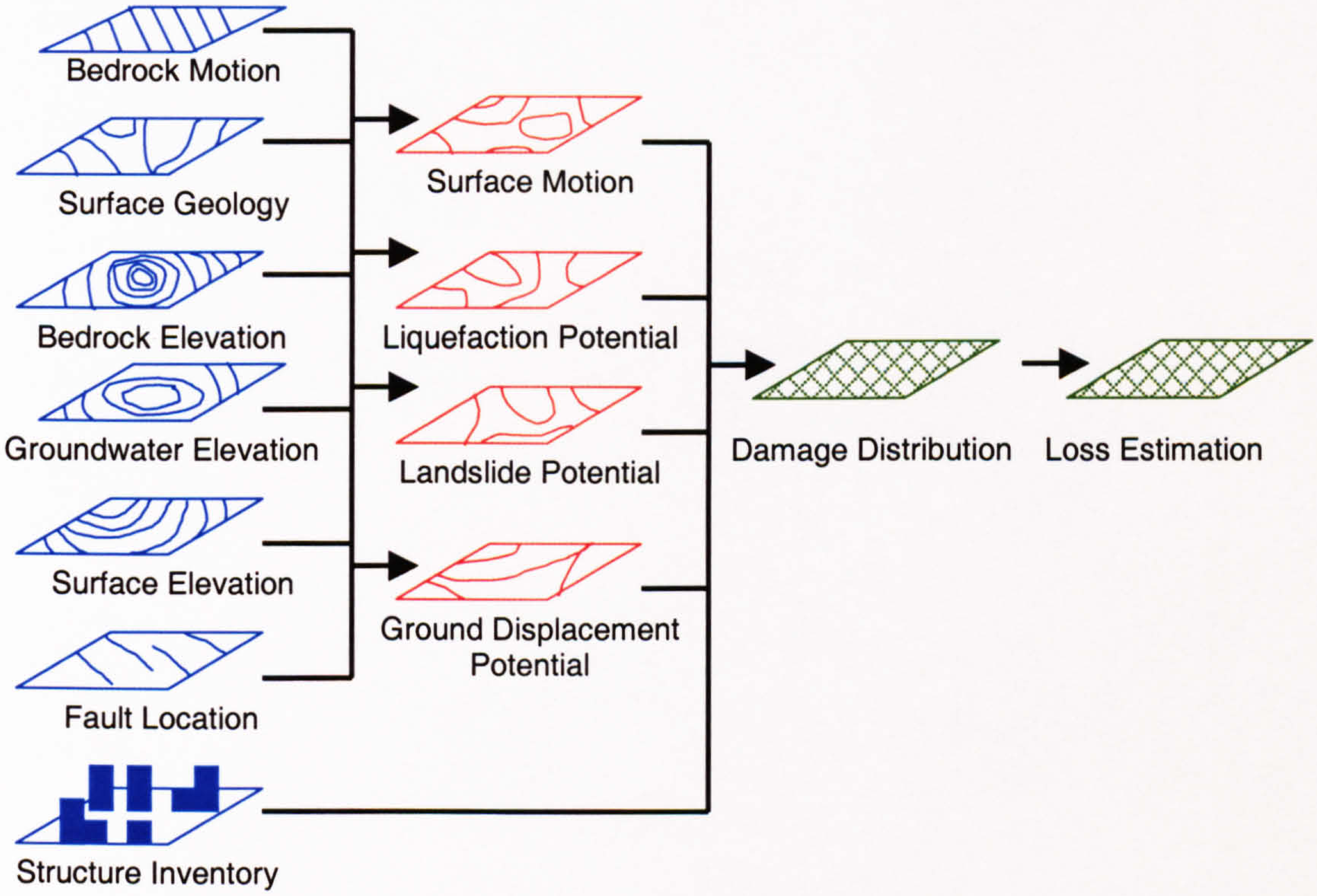


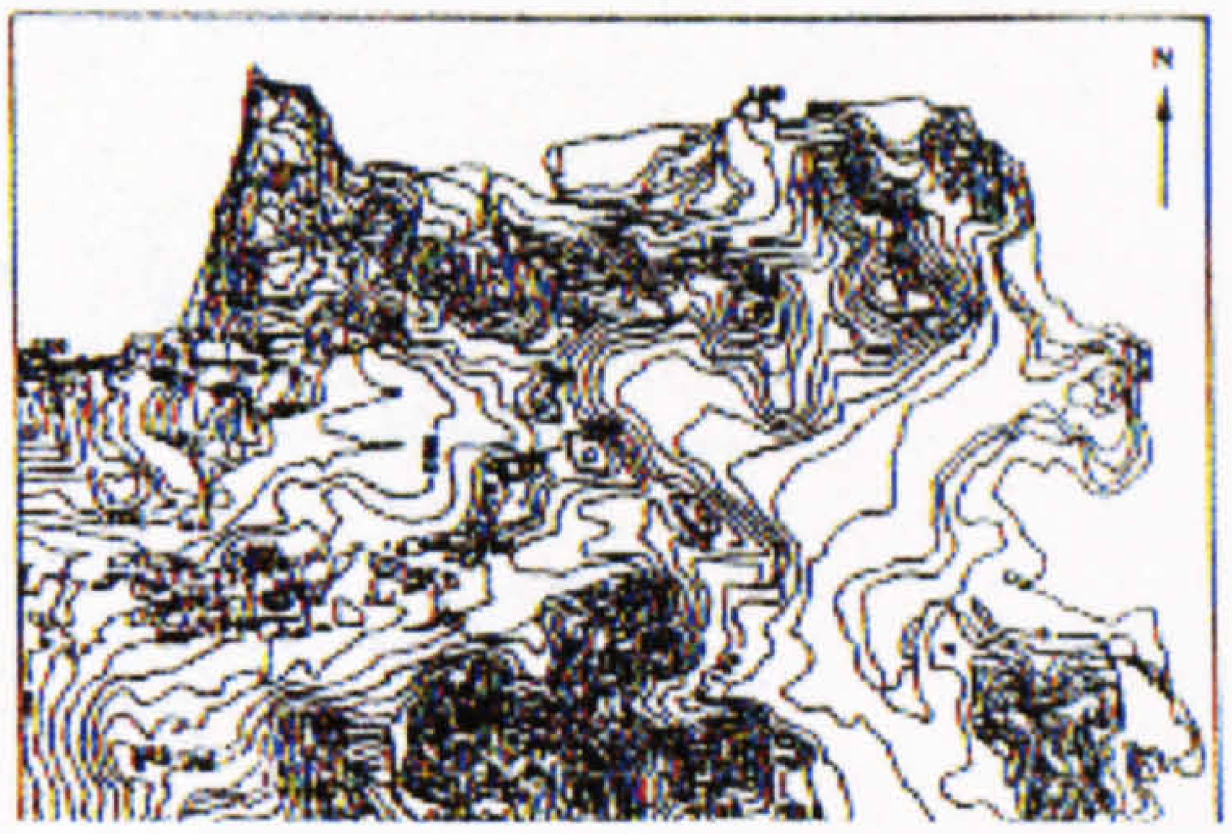
Figure A-11. Integration of seismic hazard and risk analyses through GIS (King and Kiremidjian, 1993)

In an attempt to demonstrate the capability of the GIS framework to input, manage, combine and output the analysis information King and Kiremidjian (1993) prepared the following example.

Figure A-12 illustrates a simple example of using GIS to develop preliminary estimates of dominant site period for a region in the San Francisco Bay area. In an attempt to simplify the example it was assumed that the soil deposit has uniform geologic characteristics which extend down to the bedrock level. Therefore the dominant site period was derived from:

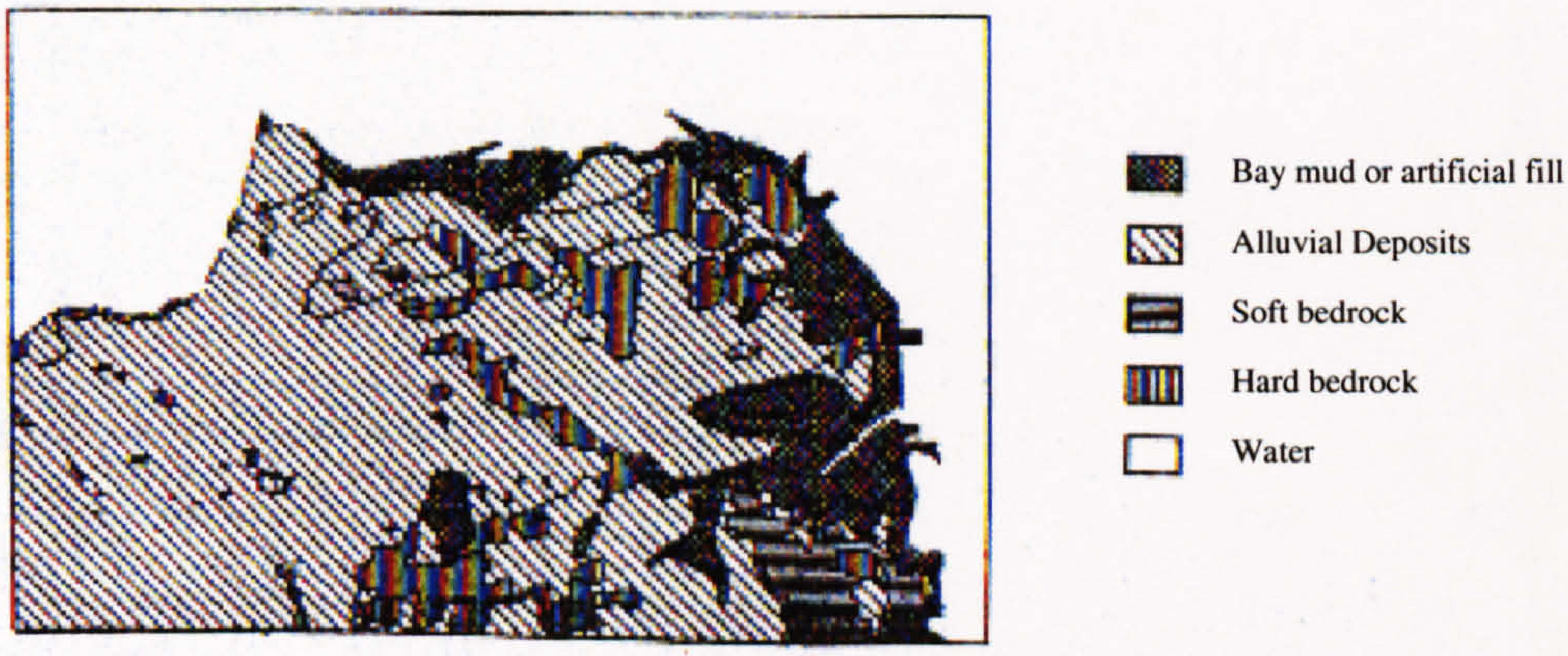
$$T = {}^{4H}\!\big/_{V_S} \qquad \textbf{(A-10)}$$

Where: H is the thickness of the soil layer
V_S is the average shear wave velocity of the soil deposit

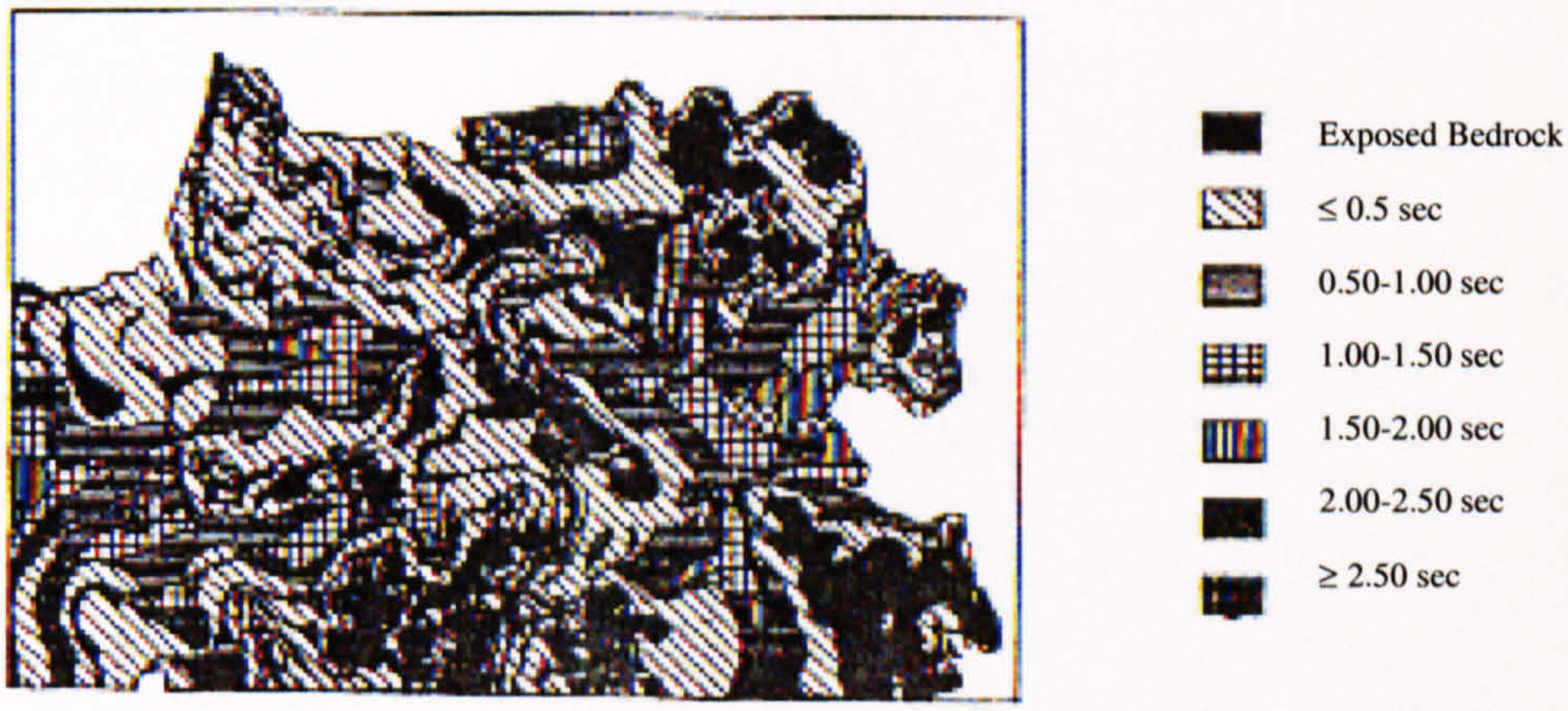


A. Map showing contours of rock elevation in the San Francisco North Quadrangle

B. Map showing contours of surface elevation in the San Francisco North Quadrangle



C. Map showing surface soil type in the San Francisco North Quadrangle



D. Map showing preliminary estimates of site dominant period in the San Francisco North Quadrangle

Figure A-12. Utilisation of GIS for the development of preliminary estimates of dominant site period for a region in the San Francisco Bay area (King and Kiremidjian, 1993)

Initially map A – bedrock elevation contours, was combined with map B – surface elevation contours, to produce a map of soil thickness in the region. Map C – surface soil type, was then used with geologic database information to relate surface soil type to an estimate of average shear wave velocity. Finally by combining the map of soil thickness to the surface soil type map based on equation A-10 map D – preliminary dominant site period was developed.

The analysis framework proposed by King and Kiremidjian (1993) is ideal both for estimating levels of seismic hazard and risk in a region and for developing and analysing several possible regional seismic hazard and risk mitigation strategies.

Noller et al. (1991), used GIS to develop seismic hazard zonation maps which would be applied in the assessment of the earthquake vulnerability of the facilities of the Pacific Gas & Electric Company. Having the locations of the PG&E Company's facilities presented as a map layer, and integrating it with various maps of fault location, slope failure and liquefaction, enables the evaluation of the exposure of the gas system to seismic hazards. Once the assessment of the seismic hazard is made then specific mitigation measures can be developed and applied.

It can therefore be concluded that a GIS with its information handling and graphics capabilities can meet each users' needs.

2.3 ACCURACY REQUIREMENTS

Hazard mitigation policies rely on the accurate assessment of the potential earthquake damage and casualty risk.

Errors and inaccuracies can occur when attempting a seismic risk assessment. These are mainly due to measurement errors, as well as model specification errors. In the assessment of seismic risk through a GIS it is possible to increase the inaccuracies, mainly due to errors in digital overlay analysis as well as vector to raster conversion error (Emmi, 1993).

2.4 CURRENT PRACTICE IN GIS-BASED SEISMIC RISK ASSESSMENT

As it was mentioned in chapter 2 the probabilistic seismic risk assessment involves:

1) the identification of the hazards' source,

2) the modelling of the earthquake recurrence,

3) the modelling of the attenuation,

4) the local site-soil interaction modelling,

and 5) the forecasting of the damage.

According to Emmi (1993) there are no applications of GIS in the identification of the hazards' source and the modelling of the earthquake recurrence. However, for the modelling of the attenuation there are numerous applications. Haslam (1991) employed the use of a GIS to model regional tectonic rebounding associated with the hydrostatic unloading of Pleistocene Lake Bonneville which enabled him to measure regional crustal elasticity, an essential parameter in seismic attenuation functions (in Emmi, 1993).

Rhea et al. (1991) rely on GIS to transform frequency-magnitude relationships, attenuation functions and source to site distance parameters into probabilistic ground motion intensity maps for the Central Mississippi Valley. Algermissen et al. (1990) did the same for a nation wide scale (in Emmi, 1993).

Emmi, (1993a) addressed the local site-soil interaction modelling in an attempt to define ground motion amplification ratios as a function of surface geologic units and pseudo-relative velocity contours (in Emmi, 1993).

As far as the forecasting of the damage is concerned, it has been dealt by various researchers (Emmi, 1993). Foster (1991) used three different sets of damage relationships in an attempt to assess property loss in the San Mateo quadrangle (in Emmi, 1993). Shah et al. (1991) developed loss estimates and insurance rates for the Californian Residential Earthquake Recovery Fund (in Emmi 1993). Emmi and Horton (1993a) used GIS-based models to show the expected casualty distributions in Salt Lake County, Utah (in Emmi, 1993). The same authors (1993b) utilised GIS to assess the benefits of a seismic retrofit policy focused on commercial unreinforced masonry structures (in Emmi, 1993).

All these illustrate the vast potential of GIS implementation in hazard mitigation policy analysis.

The considerable uncertainty surrounding the accuracy of seismic risk assessment results justifies the need for improvement in the existing methods of attenuation modelling, site-soil interaction modelling and damage forecasting (Emmi, 1993). The fact that all these, involve spatial parameters, suggests that the progress of GIS will affect their future development and accuracy and consequently the accuracy of the seismic risk assessment results.

3 MODIFIED MERCALLI (MM) INTENSITY SCALE

I Not felt by people.[1]

II Felt only by a few persons at rest, especially on upper floors of buildings.

III Felt indoors by many people. Feels like the vibration of a light truck passing by Hanging objects swing. May not be recognised as an earthquake.[2]

IV Felt indoors by most people and outdoors by a few. Feels like the vibration of a heavy truck passing by. Hanging objects swing noticeably Standing automobiles rock. Windows, dishes, and doors rattle; glasses and crockery clink. Some wood walls and frames creak.

V Felt by most people indoors and outdoors; sleepers awaken. Liquids disturbed, with some spillage. Small objects displaced or upset; some dishes and glassware broken. Doors swing; pendulum clocks may stop. Trees and poles may shake.

VI Felt by everyone. Many people are frightened, some run outdoors. People move unsteadily. Dishes, glassware, and some windows break. Small objects fall off shelves; pictures fall off walls. Furniture may move. Weak plaster and masonry D cracks.[3] Church and school bells ring. Trees and bushes shake visibly.

VII People are frightened; it is difficult to stand. Automobile drivers notice the shaking. Hanging objects quiver. Furniture breaks. Weak chimneys break. Loose bricks, stones, tiles, cornices, unbraced parapets and architectural ornaments fall from buildings. Damage to masonry D; some cracks in masonry C. Waves seen on ponds. Small slides along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged.

VIII General fright; signs of panic. Steering of vehicles is affected. Stucco falls; some masonry walls fall. Some twisting and falling of chimneys, factory stacks, monuments, towers, and elevated tanks. Frame houses move on foundations if not bolted down. Heavy damage to masonry D; damage and partial collapse of masonry C. Some damage to masonry B, none to masonry A. Decayed piles break off. Branches break from trees. Flow or temperature of water in springs and wells may change. Cracks appear in wet ground and on steep slopes.

IX General panic. Damage to well-built structures; much interior damage. Frame structures are racked and, if not bolted down, shift off foundations. Masonry D destroyed; heavy damage to masonry C, sometimes with complete collapse; masonry B seriously damaged. Damage to foundations. Serious damage to reservoirs; underground pipes broken. Conspicuous cracks in the ground. In alluvial soil, sand and mud is ejected; earthquake fountains occur and sand craters are formed.

X Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, and embankments. Large landslides. Water is thrown on banks of canals, rivers, and lakes. Sand and mud are shifted horizontally on beaches and flat land. Rails bent slightly

XI Most masonry and wood structures collapse. Some bridges destroyed. Large fissures appear in the ground. Underground pipelines completely out of service. Rails badly bent.

XII Damage is total. Large rock masses are displaced. Waves are seen on the surface of the ground. Lines of sight and level are distorted. Objects are thrown into the air.

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[1]At intensity I there may be effects from very large earthquakes at considerable distance in the form of long-period motion. These effects include disturbed birds and animals, swaying of hanging objects, and slow swinging of doors, although people will not feel the shaking and will not recognise the effects as being caused by an earthquake.

[2]Each earthquake effect is listed in the table at the level of intensity at which it appears frequently. It may be found less frequently or less strongly at the preceding (lower) level and more frequently and more strongly at higher levels.

[3]The quality of masonry or brick construction was categorised by Richter (1956) as follows: Masonry A. Good workmanship, mortar, and design; reinforced, especially laterally, and bound together by using steel, concrete, etc.; designed to resist lateral forces. Masonry B. Good workmanship and mortar; reinforced, but not designed in detail to resist lateral forces. Masonry C. Ordinary workmanship and mortar; no extreme weaknesses like failing to tie in at corners, but neither reinforced nor designed against horizontal forces. Masonry D. Weak materials, such as adobe; poor mortar; low standards of workmanship; weak horizontally.

APPENDIX B
Supplementary Data and Analysis

SUPPLEMENTARY DATA AND ANALYSIS

This appendix provides supplementary data and data analysis in support of work in chapter 3.

1 INVESTIGATION OF DEPTH

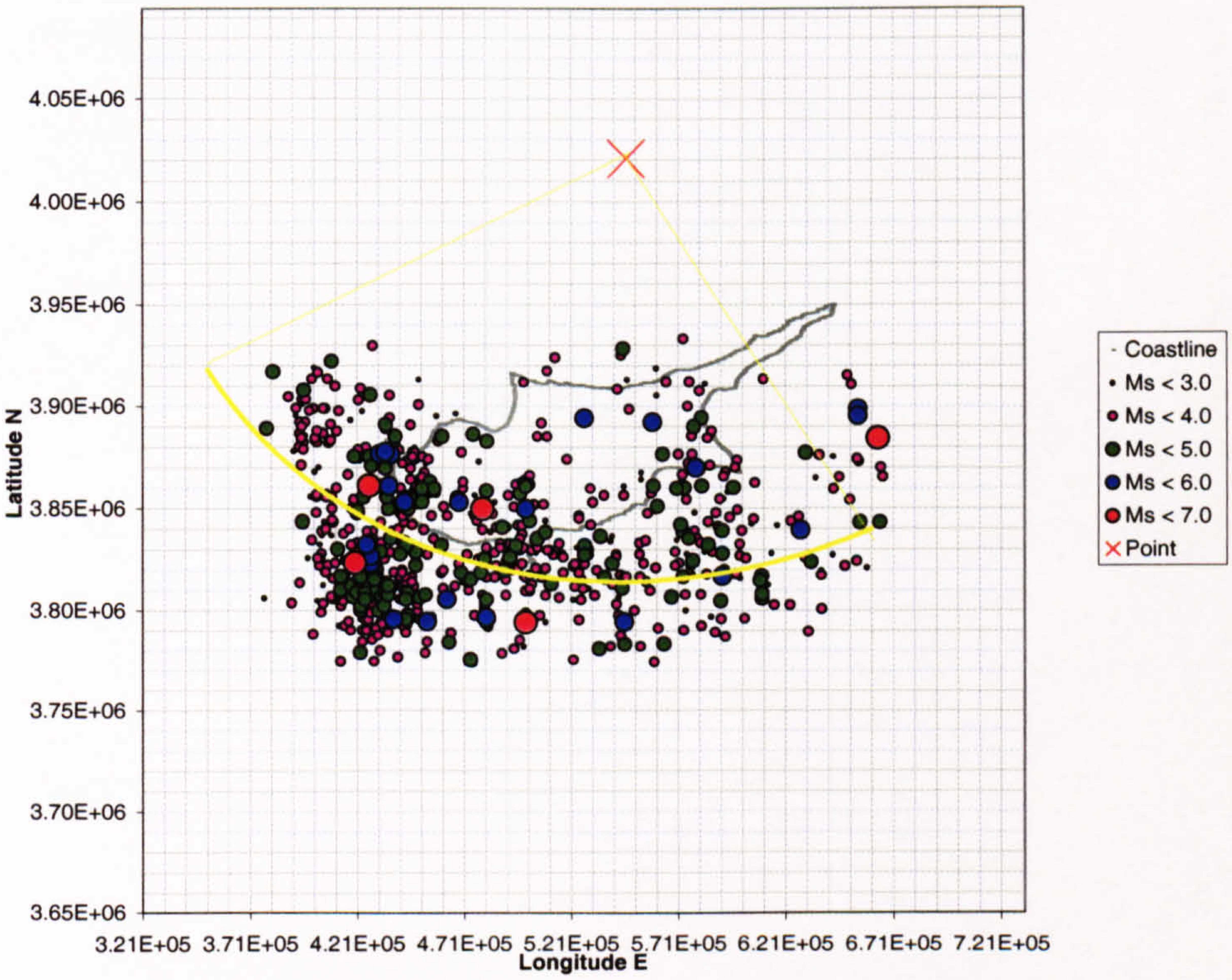


Figure B-1. Second arbitrary centre of rotation selected for the examination of the depth

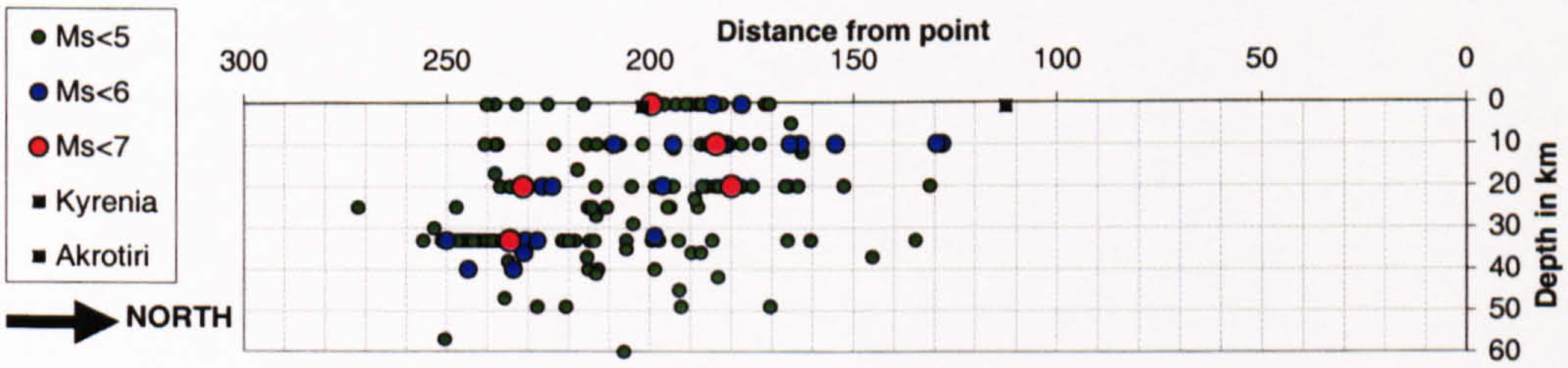


Figure B-2. Depth Distribution of earthquakes with magnitude M_S > 4.0 for the area around the position of the Cyprian Arc

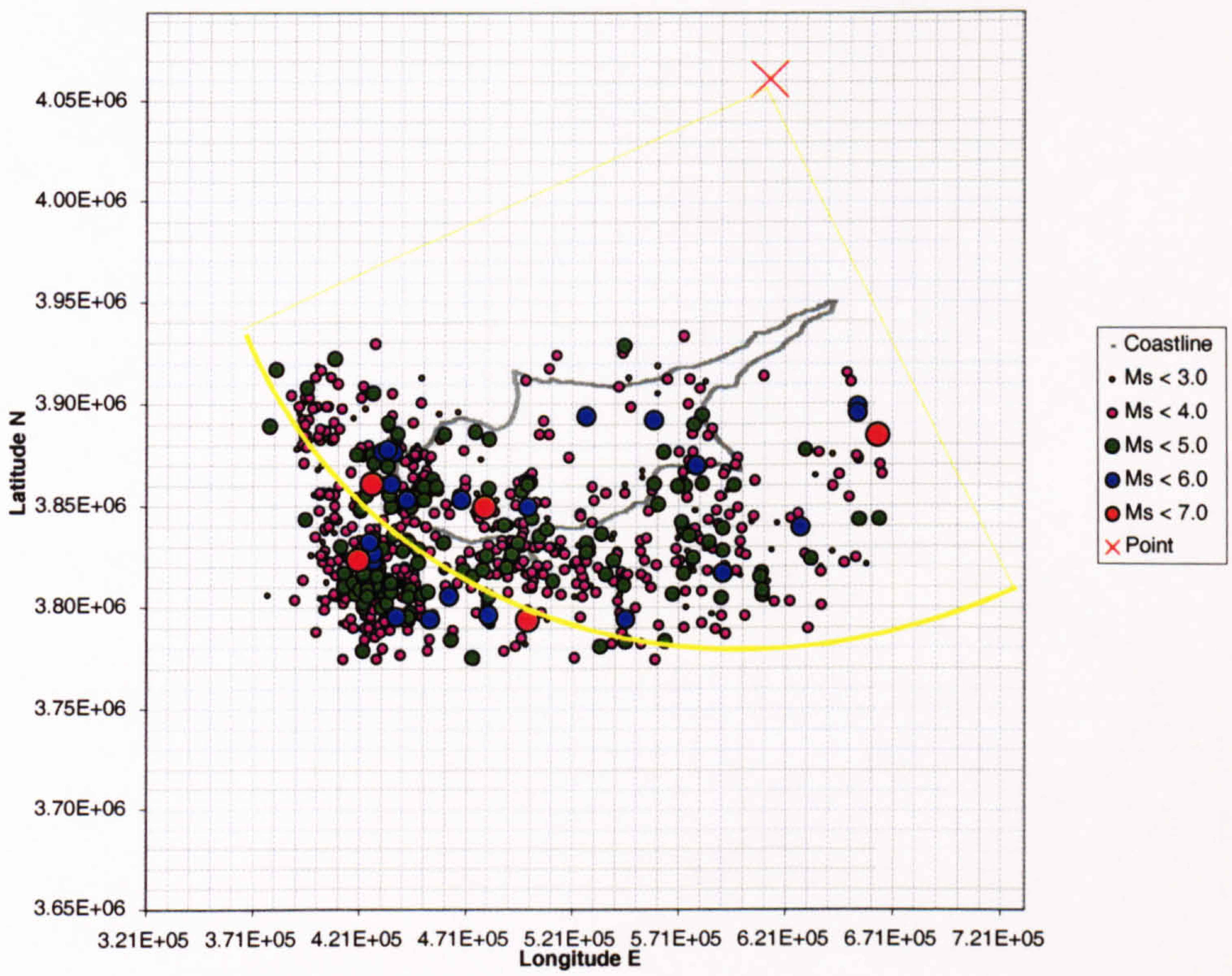


Figure B-3. Third arbitrary centre of rotation selected for the examination of the depth

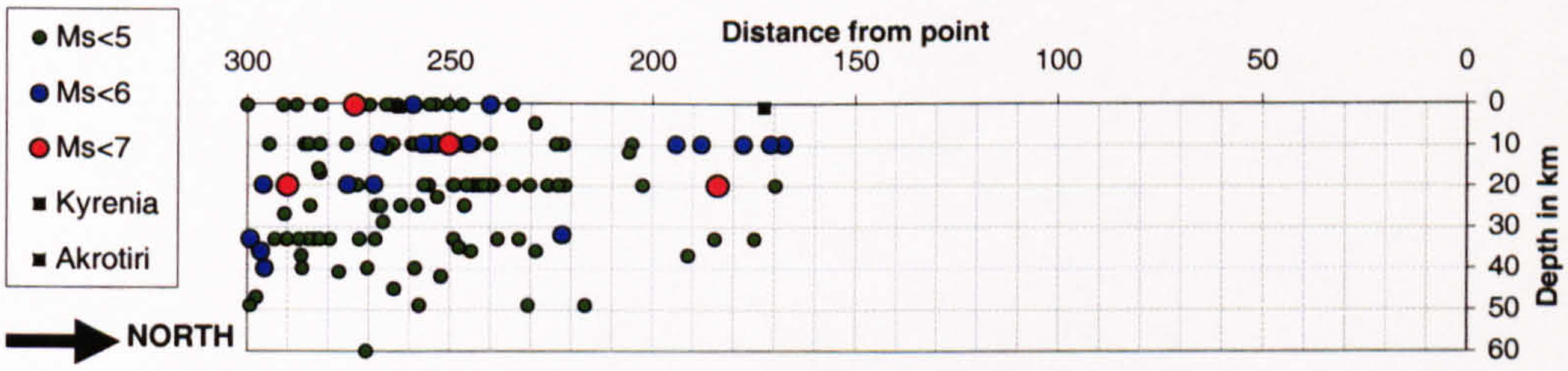


Figure B-4. Depth Distribution of earthquakes with magnitude M_S > 4.0 for the area around the position of the Cyprian Arc

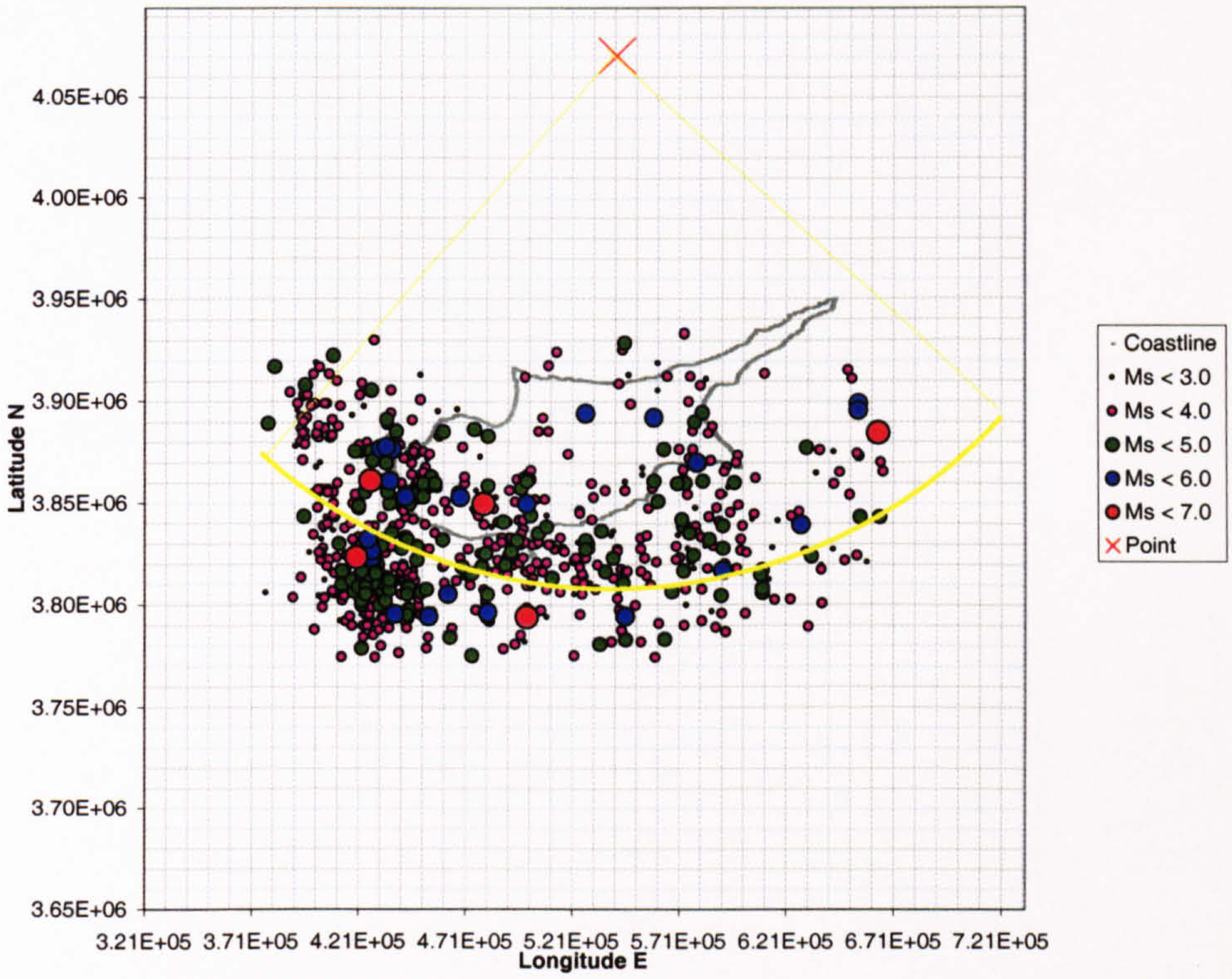


Figure B-5. Fourth arbitrary centre of rotation selected for the examination of the depth

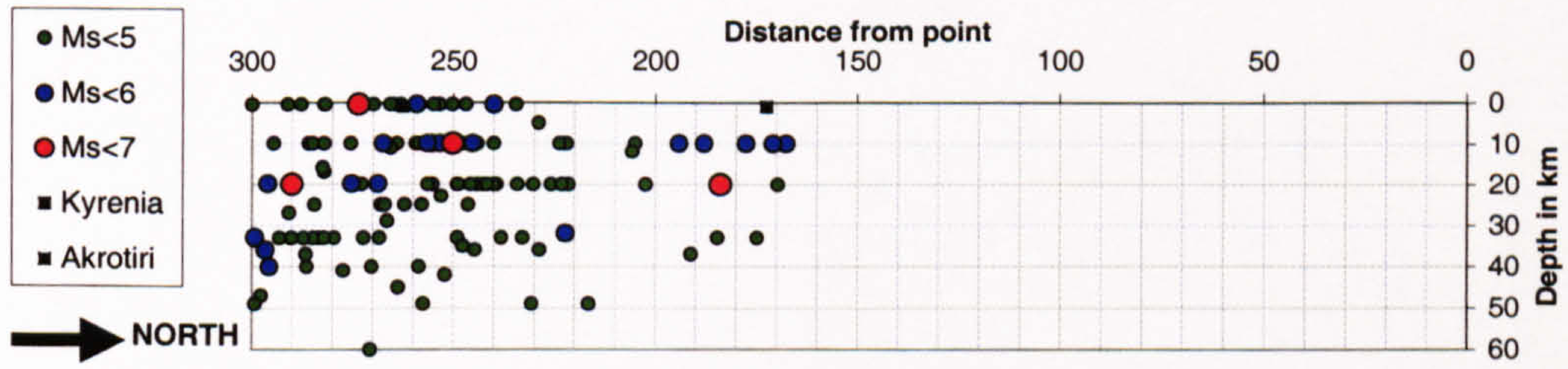


Figure B-6. Depth Distribution of earthquakes with magnitude M_S > 4.0 for the area around the position of the Cyprian Arc

2 INVESTIGATION OF ATTENUATION EQUATIONS

2.1 ATTENUATION LAWS FOR PGA

Ambraseys, 1975

(Based on data generated by earthquakes in Greece, Iran, Italy and former Yugoslavia)

$$\log(a) = 0.46 + 0.64M - 1.10\log(R) \quad \textbf{(1)}$$

Where: a is the peak horizontal ground acceleration
M is the earthquake magnitude
R is the source-site distance

Ambraseys and Bommer, 1991

(Based on data generated by earthquakes in Europe, North Africa and the Middle East)

$$\log(a) = -1.09 + 0.238M - \log\sqrt{(R^2 + 6.0^2)} - 0.00050\sqrt{(R^2 + 6.0^2)} \quad \textbf{(2a)}$$

$$\log(a) = -0.87 + 0.217M - \log\sqrt{(R^2 + h^2)} - 0.00117\sqrt{(R^2 + h^2)} \quad \textbf{(2b)}$$

Where: a is the peak horizontal ground acceleration
M is the earthquake magnitude
R is the source-site distance
h is the focal depth

Theodulides and Papazachos, 1992

(Based on data generated by earthquakes in Greece but also included 16 records from Japan and Alaska)

$$\ln a_g = 3.88 + 1.12M_S - 1.65\ln(R + 15) + 0.41S + 0.71P \quad \textbf{(3a)}$$

(for shallow earthquakes)

$$\ln a_g = 3.47 + 0.75M_W - 0.85\ln R_{CER} + 0.27S + 0.66P \quad \textbf{(3b)}$$

(for intermediate earthquakes)

Notes:

If $6.0 \le M_S \le 8.0$ then $M_W = M_S$
(Usually if $M_S \ge 5.5$ then $M_W = M_S$)

If $4.2 \le M_S \le 6.0$ then $M_W = 0.56M_S + 2.66$
$R_{CER} = \sqrt{(R^2 + h^2)}$)

Where: a is the peak horizontal ground acceleration in $cm/\sec^2$,
M_S is the surface wave earthquake magnitude,
R is the epicentral (source-site) distance in km,
h is the focal depth in km,
I_{MM} is the modified Mercalli intensity,

S is a soil term taking a value of 0 at alluvial sites, 0.5 at intermediate hardness sites and 1 at rock sites
P is zero for 50 percentile values and one for 84 percentile values

Ambraseys, 1995

(Based on data generated by earthquakes in Albania, Algeria, Bulgaria, Greece Iceland, Iran, Israel, Italy, Pakistan, Portugal, Romania, Spain, Turkey, the former USSR and former Yugoslavia)

$$\log(a) = -1.43 + 0.245M - 0.786\log\sqrt{(R^2 + 2.7^2)} - 0.0010\sqrt{(R^2 + 2.7^2)} \quad \textbf{(4a)}$$

$$\log(a) = -1.06 + 0.245M - 1.016\log\sqrt{(R^2 + h^2)} - 0.00045\sqrt{(R^2 + h^2)} \quad \textbf{(4b)}$$

$$\log(a) = -1.05 + 0.245M - 0.786\log\sqrt{(R^2 + 2.7^2)} - 0.0010\sqrt{(R^2 + 2.7^2)} - 0.15\log(V_S) \quad \textbf{(4c)}$$

Where: a is the peak horizontal ground acceleration
M is the earthquake magnitude
R is the source-site distance
h is the focal depth
V_S is a term for the site geology represented by the average shear-wave velocity (m/s)

Ambraseys, Simpson, Bommer 1996

(Based on data generated by earthquakes in Europe and adjacent regions)

$$\log(a) = -1.48 + 0.266M_S - 0.922\log(r) + 0.117S_A + 0.124S_S \quad \textbf{(5)}$$

$$r = \sqrt{(d^2 + 3.5^2)}$$

Where: a is the peak horizontal ground acceleration
M_S is the surface magnitude
r is the source-site distance
d is the shortest distance from the station to the surface projection of the fault rupture in km
S_A takes a value of 1 for stiff soil sites otherwise 0
S_S takes a value of 1 for soft soil sites otherwise 0
S_A and S_S takes a value of 0 for rock sites

2.2 ATTENUATION LAWS FOR I_{MM}

$\ln(a) = -6.558 + 0.691 I_{MM}$ for IV ≤ I_{MM} ≤ X (Trifunac and Brady, 1975) **(6)**

$\ln(a) = -7.671 + 0.721 I_{MM}$ (Bolt, 1978) **(7)**

$\ln(a) = -7.772 + 0.721 I_{MM}$ I_{MM} ≤ IX (Dowrick, 1989) **(8)**

2.3 APPLICATION OF ATTENUATION EQUATIONS

2.3.1 FURTHER VERIFICATION OF THE RESULTS

Further attempt to verify the results included the presentation of the max observed intensities and their comparison to the map of maximum observed intensities and seismic zones of the island.

By examining Figure B-7 various questions have arisen, concerning the high intensity values experienced on the Troodos massif, as well as in the area north-east of Nicosia. Further investigation in this strange pattern proved that for both cases two individual earthquakes were responsible (Figure B-8). The first earthquake occurred on the 9th of October in 1953 and had a magnitude M_S=6.1 and a depth of 10km, its epicentre was at 34.9° N and 32.2° E. The second one occurred on the 20th of January in 1941 and had a magnitude of M_S=5.9 and a depth of 10km, its epicentre was at 35.18° N and 33.65° E.

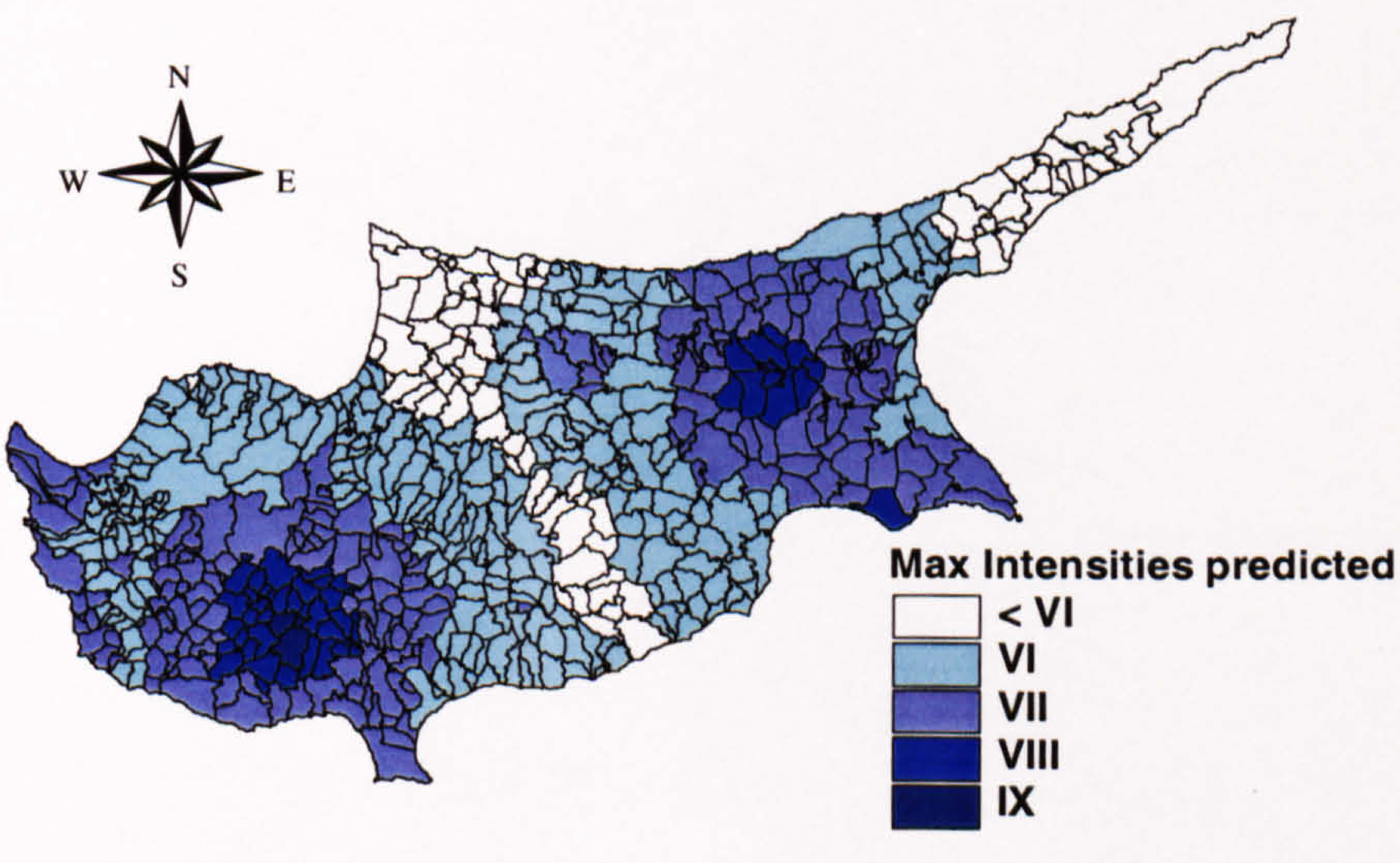


Figure B-7. Maximum predicted Intensities in the island of Cyprus from 1984 until 1998 according to Theodulidis and Papazachos (1992) equations

Various factors could be the cause of this problem. It is possible that the estimation of the magnitude of the events was not accurate but the possibility of a wrong identification of their epicentres and depths is greater.

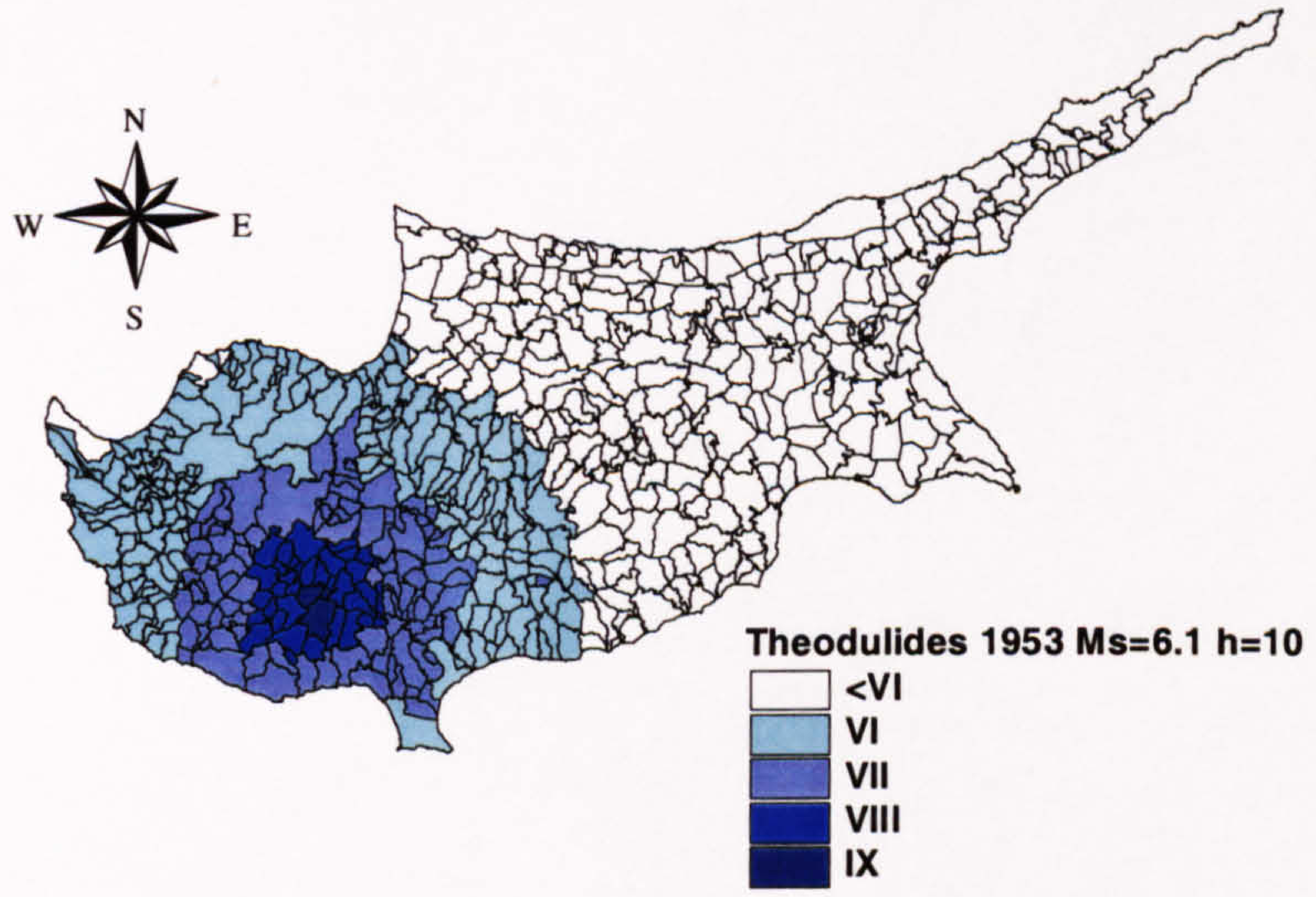


Figure B-8. Predicted Intensities from the earthquake of the 9th of October 1953 with M_S=6.1 and h = 10km according to Theodulidis and Papazachos (1992) equations

An attempt to resolve this obstacle included the assignment of a greater depth to the earthquakes. This though generated a new dilemma. Despite the fact that the intensity dropped by a point it became more spread and higher intensity was predicted in areas which previously had a considerably lower intensity values (Figure B-9).

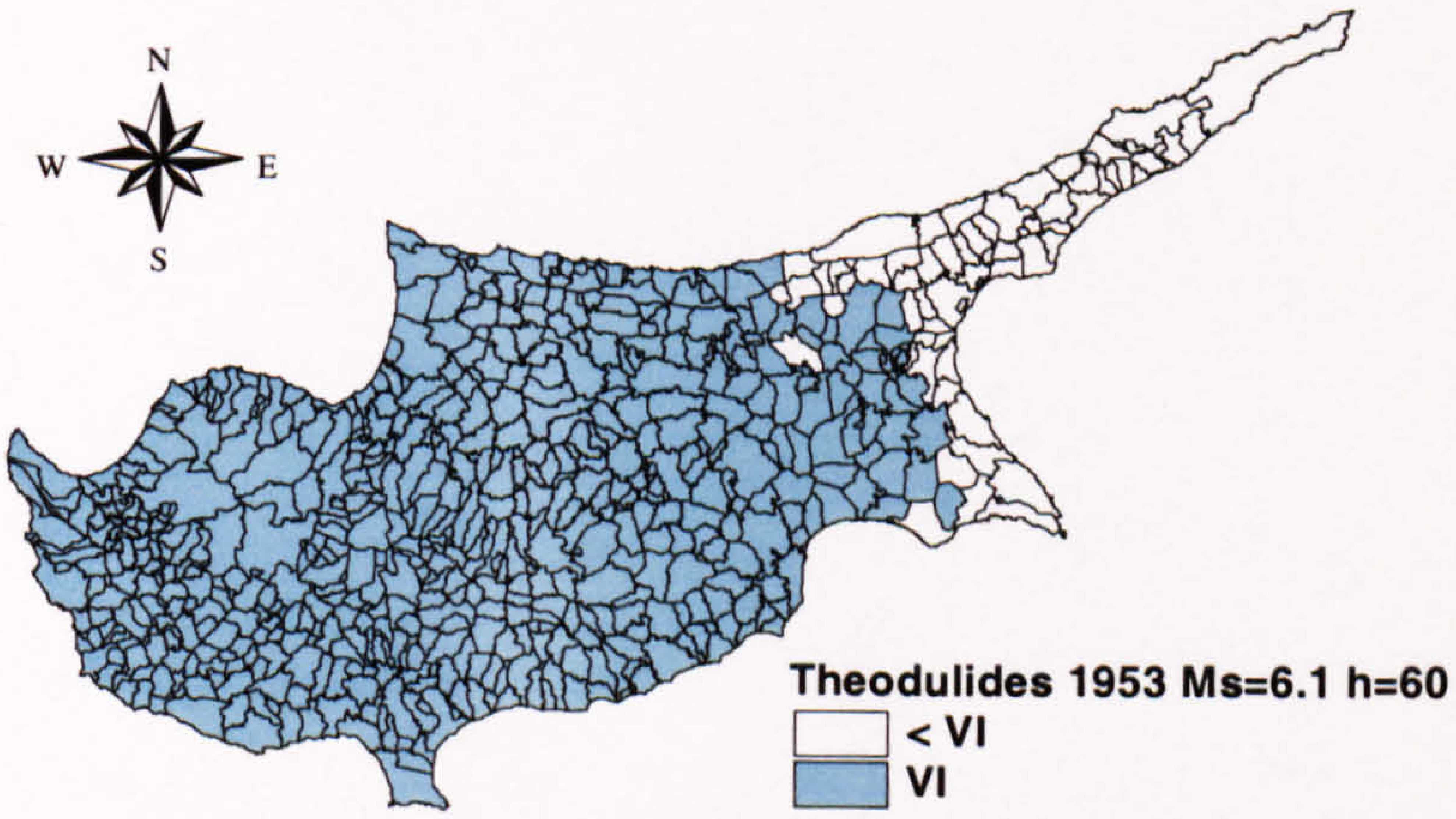


Figure B-9. Predicted Intensities from the earthquake of the 9th of October 1953 with M_S=6.1 and an imaginary h = 60km according to Theodulidis and Papazachos (1992) equations

Due to these unforeseen results it was decided to try to use some of the other attenuation equations identified in section 3.2.5.1. A first check involved the application of Ambraseys (1995) equation. This was applied for the earthquake of the 9th of October 1953 with M_S=6.1 and an h = 10km to calculate the predicted accelerations and Theodulidis and Papazachos (1992) to transform those accelerations to intensities (Figure B-10).

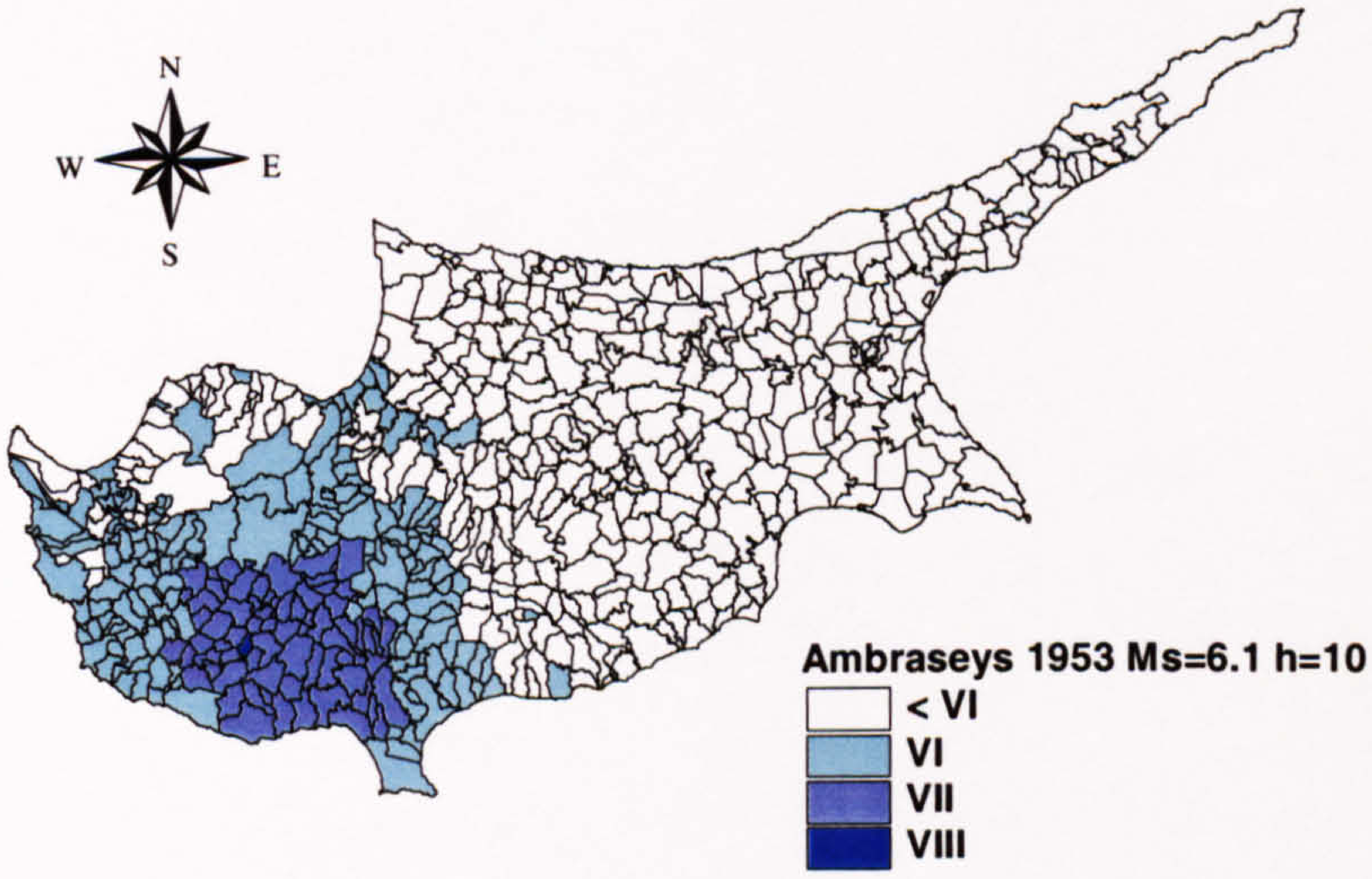


Figure B-10. Predicted Intensities from the earthquake of the 9th of October 1953 with M_S=6.1 and h = 10km according to Ambraseys (1995) equation

By applying this equation it was possible to get lower intensity values than from the Theodulidis and Papazachos (1992) relationship. This confusing situation led us to perform further comparisons of the available attenuation equations.

2.3.2 COMPARISON OF ATTENUATION EQUATIONS

From what has been presented up to now it can be concluded that the task of comparing and selecting the most appropriate attenuation law can be quite difficult. This is due to the fact that in order to derive these attenuation laws the input data used are of different quality as well as quantity and furthermore the various parameters (focal depth, magnitude, source-site distance and soil classification) are presented with different definitions. For instance Source Distances is epicentral (d_e), hypocentral (r_e), closest horizontal distance to the projection of the fault rupture at the surface (d_f) or to a horizontal plane at the focal depth (r_f). Furthermore, magnitudes can be surface wave magnitude (M_S), local magnitude (M_L), Japan meteorological agency magnitude (M_{JMA}), body-wave magnitudes (m_b) or even moment magnitude (M_o).

In general it can be said that the use of different definitions for the characterisation of the various parameters involved in the attenuation relationships would ultimately bring different uncertainties in the final result (Ambraseys and Bommer, 1995). For example, the substantial uncertainty associated with the determination of the focal depth would affect considerably the results of equations that include this parameter. Furthermore, any equation whose shape is magnitude-dependent is likely to be unrealistic. The use of different magnitude scales can also affect the equation. One other point that needs to be addressed is the importance of considering the range of applicability of each equation. The limitations for each equation have been presented in Table 3.2.

Even though it seems quite impossible to compare the results of the attenuation relationships obtained for PGA, a comparison will be attempted to explore their differences hoping that this will lead to the selection of the most appropriate equation for the island of Cyprus.

From an initial check through Table 3.2 it is apparent that equation 1 due to the limitation of earthquake magnitude M_{max} = 5.0 would not be suitable since the area of Cyprus experienced earthquakes of much greater magnitude. Since Equations 2a is an improved version of 4a, increase in the number of records used, it is expected that there will not be any significant difference when compared. According to Ambraseys and Bommer (1995) a comparison between these equations Figure B-11 showed only minor changes to the predictions which could suggest stability in their analysis.

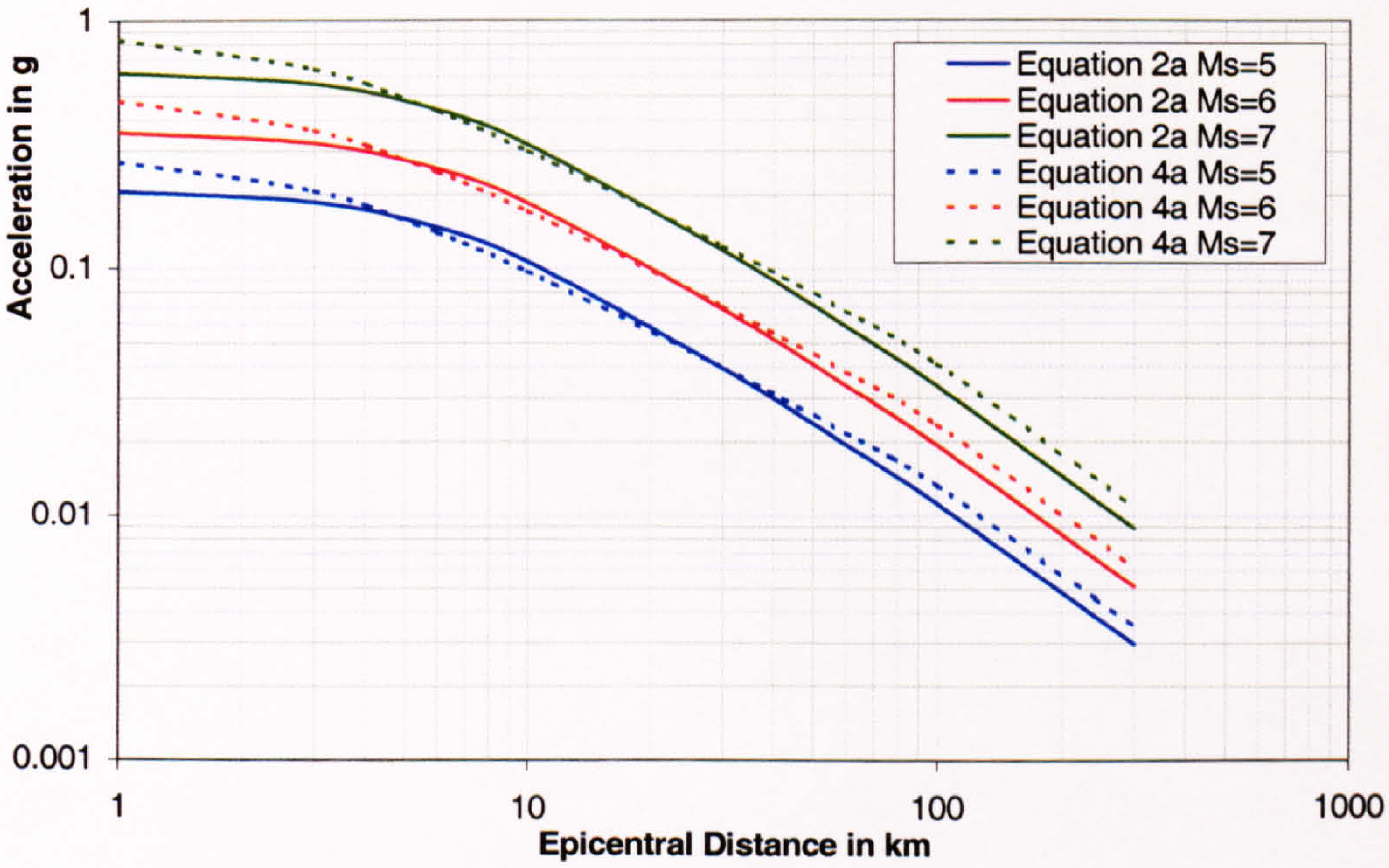


Figure B-11. Comparison of PGA predictions for Europe for shallow earthquakes of magnitudes 5, 6 and 7

Ambraseys and Bommer (1995) equation 4a has been plotted together with equation 4b for which two different depths have been applied. Whilst equation 4a includes a constant depth term, 4b includes the focal depth explicitly the two are basically a single equation. From the resulting chart (Figure B-12) it is confirmed that an earthquake of a certain magnitude at a depth h, produces a higher acceleration than an earthquake of the same magnitude but at a depth > h, at the same distance from the epicentre.

Furthermore, the greater inclination of the lines for the shallow earthquakes also confirms the fact that shallow earthquakes affect a smaller area (radius) than deeper earthquakes. The fact that there is a limitation of 25km for the depth of the earthquakes reduces the applicability of the equations for Cyprus since from the earthquake record of the island it is apparent that there are earthquakes at greater depths. Another problem related to this set of equations, is the unavailability of an equation, which would relate the accelerations to the intensities.

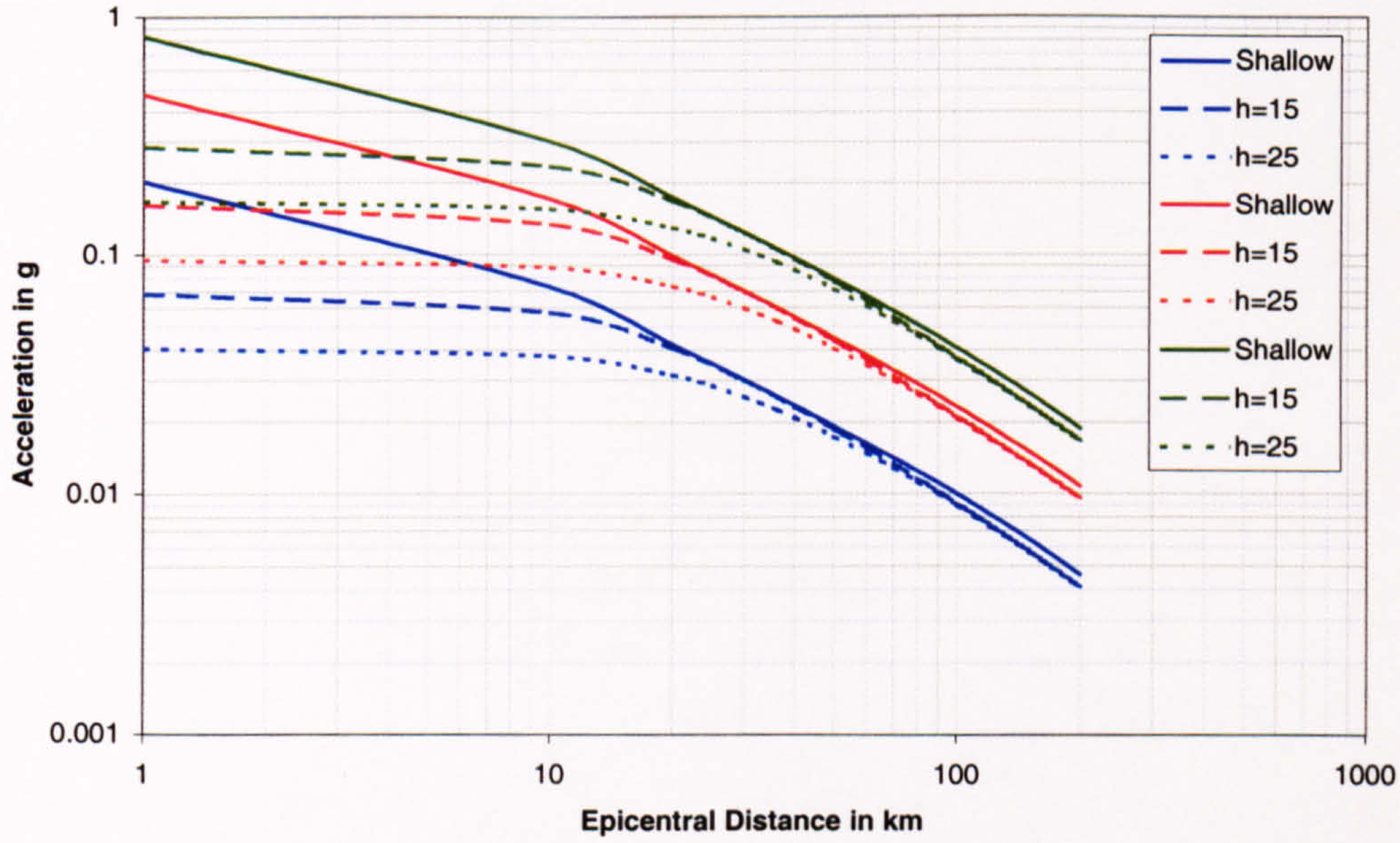


Figure B-12. Comparison of PGA predictions by Ambraseys and Bommer (1995) equations for shallow earthquakes with a constant depth term (4a) and with a focal depth of 15km and 25km (4b) for magnitudes 4.5, 6 and 7

Initially when examining Theodulidis and Papazachos (1992) equations in detail there seemed to be an inconsistency when moving from the shallow earthquakes to intermediate depth earthquakes with the acceleration Vs distance curves crossing over (Figure B-13).

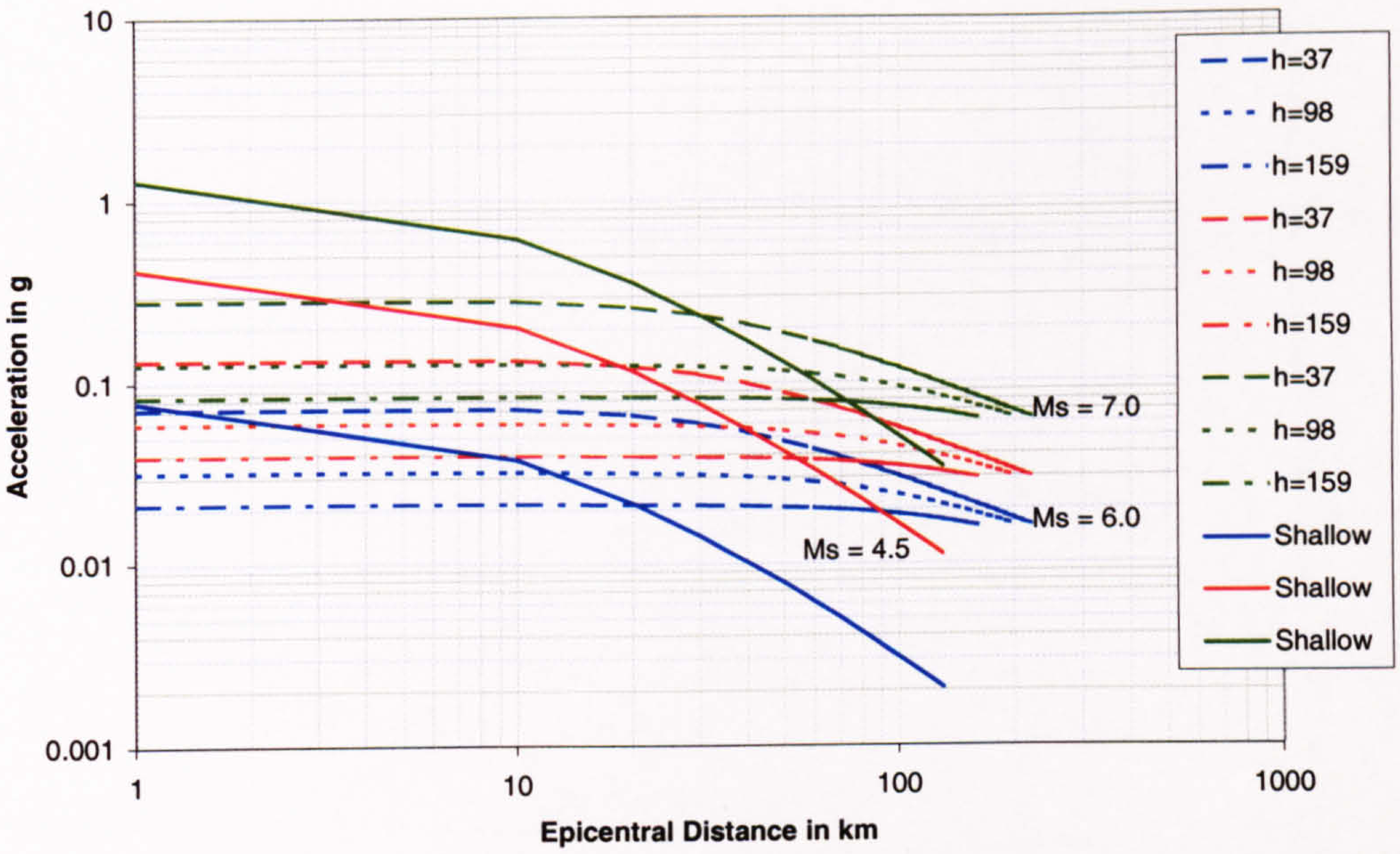


Figure B-13. Comparison of PGA predictions by Theodulidis and Papazachos (1992) equations for shallow (3a) and intermediate depth (3b) (37km, 98km and 159km) earthquakes of magnitudes 4.5,6 and 7

According to Bommer (2000) the crossing over may have a physical justification. Crouse (1991) derived an attenuation equation (eq 9) for subduction zones, by using acceleration data from earthquakes in the Northwest area of the United States and in addition to that from Alaska, Chile, Japan, Mexico and Peru.

$$\ln(a) = 6.36 + 1.76M - 2.73\ln(R + 1.58e^{0.608M}) + 0.0092h \qquad \textbf{(9)}$$

In this relationship the last term is a function of depth and by being positive it reflects the fact that the deeper the earthquake, the greater the proportion of the travel path that will be through high-velocity, low-absorption layers of the Earth. This though does not necessarily justify the crossing-over, which exists in the Theodulidis and Papazachos (1992) equations.

Bommer (2000) suggested the use of Ambraseys (1995) equations derived for shallow earthquakes in Europe, based on the fact that there is no evidence for shallow earthquakes recognising borders between Mediterranean countries and Theodulidis and Papazachos (1992) for the subduction earthquakes, or another equation derived specifically for subduction regions. By using this mixture of equations the crossing-over still exists (Figure B-14).

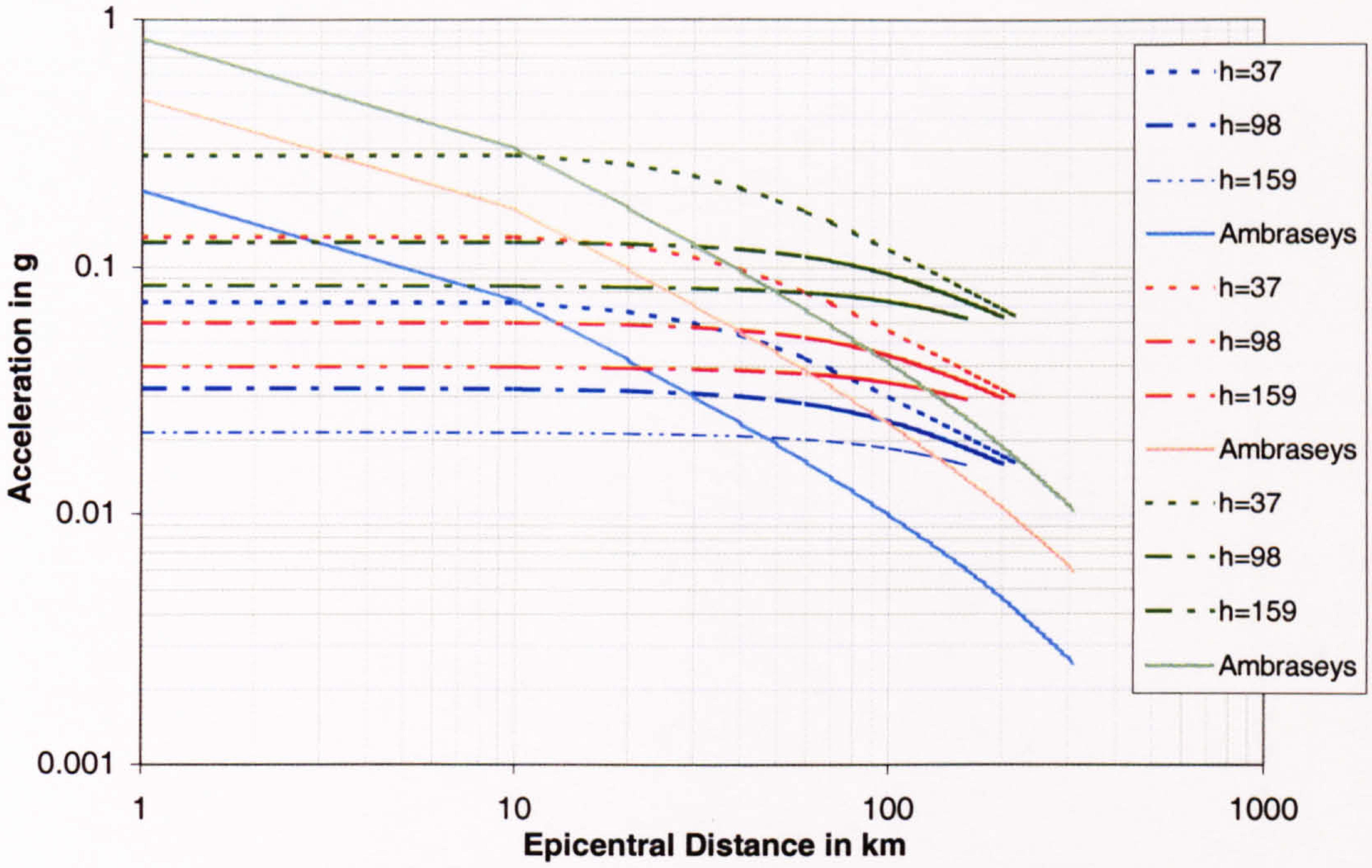


Figure B-14. Comparison of Theodulidis and Papazachos (1992) equation (3b) for intermediate depth earthquakes and Ambraseys (1995) equation (4a) for shallow earthquakes

Both equation (3a) of Theodulidis and Papazachos (1992) and equation (4a) of Ambraseys (1995) are intended for shallow earthquakes and have a constant depth term. By comparing the two it was possible to identify that for the cases of M_S=6.0 and M_S=7.0, (3a) seems to be a better solution since the crossing-over would occur at a greater distance however for magnitude M_S=4.5, (4a) is by far the most suitable.

According to Bommer (2000) by using the Ambraseys, Simpson and Bommer (1996) equation (5) it would give results close to those of Ambraseys (1995) so the cross-over would still appear. However, equation (5) includes a soil classification term and for the purposes of our research one could say that it has an advantage to equation (4a). On the other hand, equation 4c which is part of the fourth equation set involves a term which deals with the site geology unfortunately it is represented by the average shear-wave velocity, a type of data which are not available for Cyprus. By comparing the three equations 3a, 4a and 5 it appears that 5 gives results close to those of 4a with slight improvement for M_S= 6.0 and 7.0 (Figure B-15).

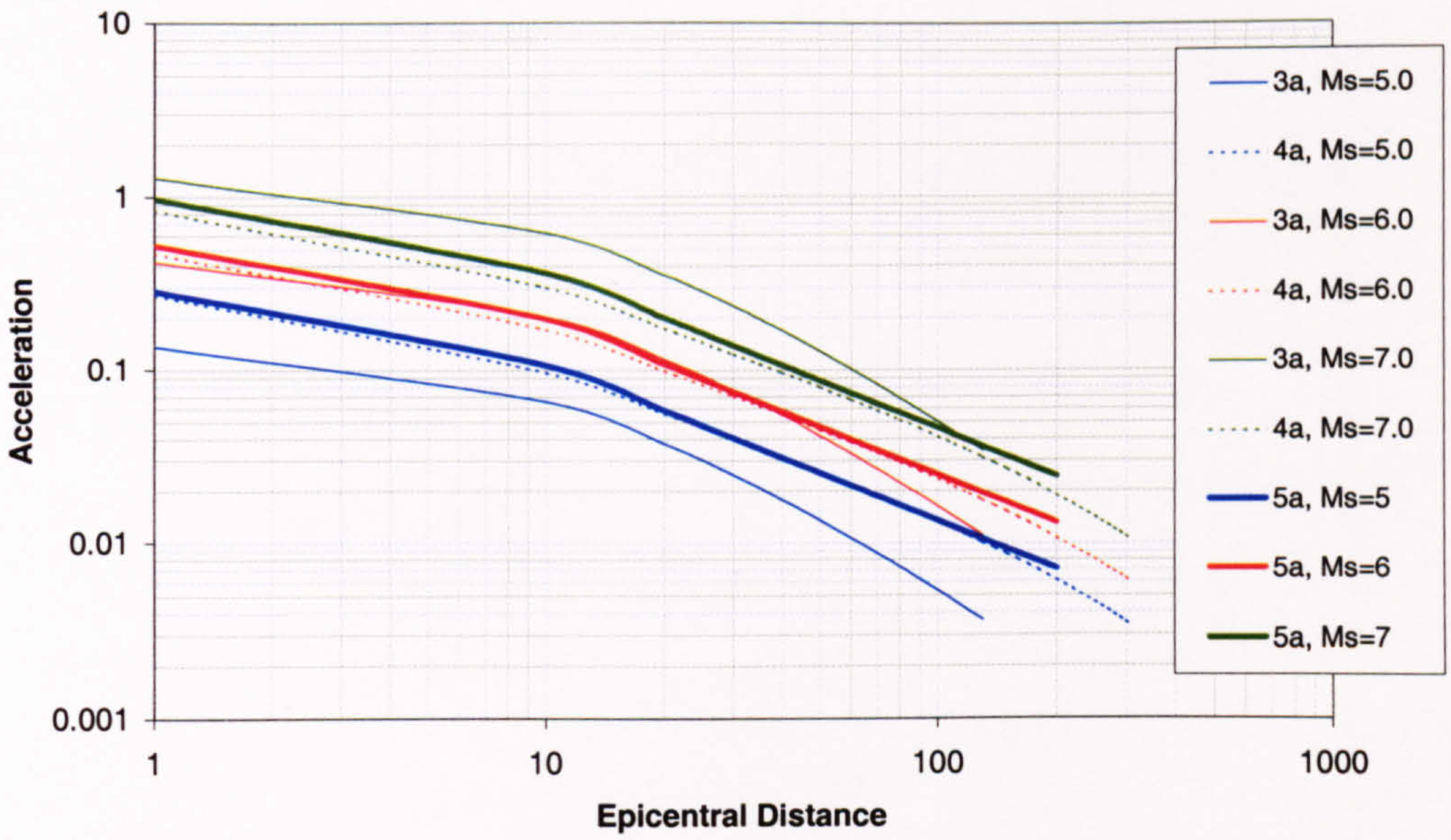


Figure B-15. Comparison of Theodulidis and Papazachos (1992) equation (3a) Ambraseys (1995) equation (4a) and Ambrasey, Simspon and Bommer (1996) equation 5 for earthquake magnitudes M_S of 5.0, 6.0 and 7.0

3 INVESTIGATION OF BUILDING STOCK

3.1 TYPE OF LIVING QUARTERS

Conventional Dwelling: is defined as a room or suite of rooms and its accessories, in a permanent building, which by the way, it has been build/rebuilt/converted, is designed for habitation by one household all the year round and is not at the time of the census used wholly for non-residential purposes. It should have direct access to the street or via a garden or grounds or a common space within the building (staircase, passage, gallery etc).

Improvised Housing Unit: is an independent, improvised shelter or structure build or crude materials, without a predetermined plan for the purpose of habitation by one household. An improvised housing unit is enumerated if it is used as living quarters at the time of the Census.

Other Housing Units not Intended for Habitation: These include premises in permanent buildings such as barns, garages, warehouses etc. which have not been built/rebuilt/converted or otherwise arranged for habitation but are actually used as living quarters at the time of the Census.

Living Quarters other than Housing Units: These are permanent structures which provide lodging on a fee basis. All rooms in hotels/boarding houses/hotel apartments rented as permanent residences were included. A list of all hotel apartments registered with the Cyprus Tourism Organisation was made available to the enumerators. Tourist apartments not registered as hotel apartments with the Cyprus Tourism Organisation were classified as conventional dwellings.

Type of Building for Conventional Dwellings: Single House/ Single Dwelling: is a structure containing one housing unit, built on a separated plot of land with direct access to the street. If the housing unit was adjoining to a shop or office on the ground floor the dwelling was still classified as a single house.

Semi-detached or doublex: is a building built on one plot of land but comprising of two independent housing units attached to each other vertically or horizontally. These housing units could have direct access to the street or via a common space within the building.

Row Houses: are attached housing units having at least one wall or part of a wall in common. Such constructions are very common in the old parts of towns and villages.

Back Yard House: is a housing unit found on the same plot of land with another principal house, with direct access to the street or through the yard. Usually it is built at the far end of the yard.

Apartment Blocks: is a structure built on a single plot of land comprising of three or more housing units with direct access to the street or via a common place in the building.

Dwellings in a Partly Residential Building: are housing units in a building comprised of both housing units for habitation and other units for other uses such as business and commercial purposes (i.e. offices, shops).

Room: is defined as a space in a housing unit enclosed by walls reaching from the floor to the ceiling or roof or at least to a height of 2 metres above the ground, of a size large enough to hold a bed for an adult (4 square metres at least). Thus normal bedrooms, dining rooms, living rooms, habitable cellars, kitchens and other separate spaces used or indented for habitation are included by definition in the number of rooms. Corridors, verandas, lobbies, bathrooms, and toilets, even if more than 4 square metres do not count as rooms.

SOURCE
Republic of Cyprus
Census of Population 1992
Volume II – Housing units and households
Part A – All Districts
Department of Statistics and Research Ministry of Finance
Page 17

3.2 TYPES OF RESIDENTIAL BUILDINGS

Residential Buildings: A building should be regarded as residential when the major part of the building (i.e. more than half of its gross floor area) is used for dwelling purposes.

Ground-oriented Residential Buildings: This category includes all types of houses, (detached, semi-detached, terraced houses, houses built in a row, etc.), each dwelling of which has its own entrance directly from ground surface.

Other Residential Buildings: This category includes all types of buildings other than ground-oriented residential buildings as defined above.

Single House: Is a structure containing only one housing unit, built on a separate plot of land with direct access to the street.

Apartment Blocks: Is a structure built on a single plot of land comprising of three or more housing units with direct access to the street via a common place in the building.

Stone Structure: Houses and Apartment Blocks constructed with stones.

Adobe Structure: Houses and Apartment Blocks constructed with mud-bricks.

Reinforced Concrete Structure: Houses and Apartment Blocks where the bearing structure is constructed with reinforced concrete. This category also includes buildings whose walls are made out of concrete blocks.

SOURCES

1. *Construction and Housing Statistics 1994*
   Department of Statistics and Research Ministry of Finance
   Republic of Cyprus Pages 38-39
2. RESEARCH PROGRAMME – Earthquake Resistance and strengthening of the existing buildings in Cyprus
   Strategic Evaluation of the earthquake risk and strengthening of the existing buildings in Cyprus
   Stage 1: Evaluation of the available data for the existing buildings in Cyprus
   KORONIDA Centre for research and Development Ltd

3.3 STATISTICS ON BUILDING STOCK AND COST OF CONSTRUCTION

Table B-1. Conventional Dwellings (Occupied & Unoccupied) period of construction, type of building and urban residence (Department of Statistics and Research of the Ministry of Finance, 1992)

Occupancy status and period of construction	TYPE OF BUILDING								
	Total	Single House	Semidetached or doublex	Row houses	Backyard houses	Apartment blocks	In a partly residential Building	Other	Not stated
TOTAL	148567	44208	29263	14805	7615	34199	18141	35	301
Before 1950	9888	4472	973	2761	955	262	447	1	17
1950-1959	8147	3787	1620	656	1084	424	556	5	15
1960-1969	15768	6199	4169	380	1963	1725	1312	3	17
1970-1979	35919	8962	6993	5216	1750	8441	4521	3	33
1980-1989	61780	15354	12036	4715	1493	18686	9422	17	57
1990-1992	15066	4979	3169	1006	242	4093	1560	6	11
Not stated	1999	455	303	71	128	568	323	0	151
USUAL RESIDENCE	124312	40563	27132	12747	6535	24259	12826	35	215
Before 1950	8388	3910	852	2230	818	225	340	1	12
1950-1959	7316	3496	1525	586	911	364	416	5	13
1960-1969	14322	5841	3885	341	1627	1550	1059	3	16
1970-1979	32447	8570	6612	4999	1526	7202	3504	3	31
1980-1989	49810	14304	11419	4107	1352	12262	6297	17	52
1990-1992	10791	4207	2615	456	216	2296	988	6	7
Not stated	1238	235	224	28	85	360	222	0	84
UNOCCUPIED CONVENTIONAL DWELLING	24255	3645	2131	2058	1080	9940	5315	0	86
Before 1950	1500	562	121	531	137	37	107	0	5
1950-1959	831	291	95	70	173	60	140	0	2
1960-1969	1446	358	284	39	336	175	253	0	1
1970-1979	3472	392	381	217	224	1239	1017	0	2
1980-1989	11970	1050	617	608	141	6424	3125	0	5
1990-1992	4275	772	554	550	26	1797	572	0	4
Not stated	761	220	79	43	43	208	101	0	67

Table B-2. Conventional Dwellings (Occupied & Unoccupied) period of construction, type of building and rural residence (Department of Statistics and Research of the Ministry of Finance, 1992)

Occupancy status and period of construction	TYPE OF BUILDING								
	Total	Single House	Semidetached or doublex	Row houses	Backyard houses	Apartment blocks	In a partly residential Building	Other	Not stated
TOTAL	83363	56200	6247	12381	1914	5091	1363	7	160
Before 1950	23831	13208	1372	8578	509	81	58	0	25
1950-1959	5106	4011	367	623	72	20	7	1	5
1960-1969	7231	5910	584	476	173	50	34	0	4
1970-1979	14356	11896	1053	634	364	282	119	3	5
1980-1989	22387	15441	2080	1211	648	2184	806	1	16
1990-1992	7595	4815	631	512	133	1272	224	1	7
Not stated	2857	919	160	347	15	1202	115	1	98
USUAL RESIDENCE	59431	45072	4487	6645	1613	999	536	6	73
Before 1950	15381	9181	758	4923	447	11	42	0	19
1950-1959	3846	3112	224	431	60	9	6	1	3
1960-1969	5867	4939	443	264	146	38	33	0	4
1970-1979	12700	10715	891	511	313	161	102	3	4
1980-1989	16843	13349	1731	403	523	563	258	1	15
1990-1992	4413	3527	410	93	114	184	80	1	4
Not stated	381	249	30	20	10	33	15	0	24
UNOCCUPIED CONVENTIONAL DWELLING	23932	11128	1760	5736	301	4092	827	1	87
Before 1950	8450	4027	614	3655	62	70	16	0	6
1950-1959	1260	899	143	192	12	11	1	0	2
1960-1969	1364	971	141	212	27	12	1	0	0
1970-1979	1656	1181	162	123	51	121	17	0	1
1980-1989	5544	2092	349	808	125	1621	548	0	1
1990-1992	3182	1288	221	419	19	1088	144	0	3
Not stated	2476	670	130	327	5	1169	100	1	74

Table B-3. Period of construction of residential units (Hadjiloizi, 1998)

	Up to 1947	1947-1960	1961-1970	1971-1980	1981-1990	1991-1996	TOTAL
NICOSIA							
RC Houses	715	5307	7882	16497	16742	9794	56937
RC Apartments	71	1026	2603	8976	7351	3060	23087
Stone Houses	3148	1443	139	48	9	0	4787
Stone Apartments	241	266	18	8	0	0	533
Adobe Houses	7495	2811	243	62	13	0	10624
Adobe Apartments	150	64	3	2	0	0	219
FAMAGUSTA							
RC Houses	36	480	1031	3087	3068	2357	10059
RC Apartments	2	14	63	390	2295	2479	5243
Stone Houses	751	431	13	31	0	0	1226
Stone Apartments	7	8	0	1	0	0	16
Adobe Houses	52	6	6	1	0	0	65
Adobe Apartments	0	0	0	0	0	0	0
LARNACA							
RC Houses	240	1181	2209	7249	8768	5281	24928
RC Apartments	13	99	205	1787	4087	3558	9749
Stone Houses	2436	457	52	90	18	0	3053
Stone Apartments	54	22	0	0	0	0	76
Adobe Houses	3723	883	105	15	2	0	4728
Adobe Apartments	50	12	0	0	0	0	62
LIMASSOL							
RC Houses	1051	4786	7642	10400	12308	8384	44571
RC Apartments	46	429	1091	4131	8298	2628	16623
Stone Houses	7598	2915	457	154	29	0	11153
Stone Apartments	143	147	17	0	0	0	307
Adobe Houses	2261	661	38	8	2	0	2970
Adobe Apartments	44	10	1	0	0	0	55
PAPHOS							
RC Houses	160	1385	1615	2734	4629	3634	14157
RC Apartments	0	30	58	434	3227	2884	6633
Stone Houses	5611	2436	383	102	28	0	8560
Stone Apartments	24	22	1	5	7	0	59
Adobe Houses	302	69	5	0	0	0	376
Adobe Apartments	4	0	0	0	0	0	4
TOTAL	36428	27400	25880	56212	70881	44059	260860
PANCYPRIAN							
RC Houses	2202	13139	20379	39967	45515	29450	150652
RC Apartments	132	1598	4020	15718	25258	14609	61335
Stone Houses	19544	7682	1044	425	84	0	28779
Stone Apartments	469	465	36	14	7	0	991
Adobe Houses	13833	4430	397	86	17	0	18763
Adobe Apartments	248	86	4	2	0	0	340

Table B-4. Number of buildings based on type and height for all the districts (Hadjiloizi, 1998)

TYPE	NICOSIA	FAMAGUSTA	LARNAC	LIMASSOL	PAPHOS	PANCYPRIAN
OTHER						
Stone Houses	4787	1226	3053	11153	8560	28779
Stone Apartment Blocks	88	9	12	51	9	169
Adobe Houses	10624	65	4728	2970	376	18763
Adobe Apartment Blocks	36	0	10	9	1	56
REINFORCED CONCRETE HOUSES						
Ground floor	12464	2202	5457	9757	3099	32979
Ground floor +1	38941	6903	17041	30454	9700	103039
Ground floor +2	6509	1174	2842	5064	1636	17225
REINFORCED CONCRETE APARTMENTS						
Ground floor +3	827	188	349	596	237	2197
Ground floor +4	316	71	133	227	90	837
Ground floor +5	52	11	21	37	14	135
Ground floor +6	30	6	12	21	8	77
Ground floor +7	14	3	6	10	4	37
Ground floor +8	3	0	1	2	1	7
TOTAL	74691	11858	33665	60351	23735	204300
STONE	28948					
ADOBE	18819					
REINFORCED CONCRETE	156533					

Table B-5. Cost of Construction and number of completed residential buildings from 1974-1982 for the whole island based on type of construction and constant 1982 prices (Hadjiloizi, 1998)

COST	REINFORCED CONCRETE	Adobe	STONE
Less than £1000	671	3	17
£1000 - £5000	7515	26	129
£5000 - £10000	8603	7	48
£10000 - £15000	7931	3	15
£15000 - £20000	3892	0	10
£20000 - £30000	1568	0	6
£30000 - £50000	359	0	2
Above £50000	91	0	0
Average Cost	26817	3708	5269
TOTAL NO OF BUILDINGS	30630	39	227

Table B-6. Cost per house and apartment for each town from 1990-1996 (Hadjiloizi, 1998)

	NICOSIA		FAMAGUSTA		LARNACA		LIMASSOL		PAPHOS	
YEAR	Houses	Apartments	Houses	Apartments	Houses	Apartments	Houses	Apartments	Houses	Apartments
1990	41110	19973	30127	12349	36869	13940	36813	17118	41382	12711
1991	46494	24882	33626	13884	37435	15541	39893	18126	37875	16596
1992	51780	26605	40817	14356	36542	16128	41427	20120	40936	17115
1993	50659	35064	31745	16592	52617	19056	51192	23272	50020	19966
1994	62500	35197	63952	19577	56050	25506	54210	28528	53501	20984
1995	67028	38134	66011	23328	61861	27932	64586	34751	56521	25268
1996	71980	38787	58860	23458	62364	31694	64960	33970	64300	34320

Table B-7. Percentage Change of the Consumer Price Index, 1960-1999 (Department of Statistics and Research of the Ministry of Finance)

Year	%	Year	%
1960	0.8	1980	19.5
1961	-0.6	1981	10.8
1962	0.1	1982	6.4
1963	2.0	1983	5.1
1964	-0.4	1984	6.0
1965	0.3	1985	5.0
1966	0.5	1986	1.2
1967	0.7	1987	2.8
1968	3.8	1988	3.4
1969	2.4	1989	3.8
1970	2.4	1990	4.5
1971	4.2	1991	5.0
1972	4.8	1992	6.5
1973	7.8	1993	4.9
1974	16.2	1994	4.7
1975	4.6	1995	2.6
1976	3.8	1996	3.0
1977	7.2	1997	3.6
1978	7.4	1998	2.2
1979	9.5	1999	1.7

Table B-8. Urban areas according to the Construction and Housing statistics of 1994 (Department of Statistics and Research of the Ministry of Finance, 1994)

	TOWNS			
	LEFKOSIA	**LARNACA**	**LEMESOS**	**PAPHOS**
Municipalities	Lefkosia Agios Dometios Egkomi Strovolos Aglangia Lakatameia Lakkia	Larnaca Aradippou	Lemesos Kato Polemidia Mesa Geitonia Agios Athanasios	Paphos
Other	Geri Anthoupoli Refugee housing estate	Livadia Dromolaxia Meneou Coastal zone of Oroklini Pyla	Amathounta Germasogeia Pano Polemidia Ypsonas	Geroskipou Agia Marinouda Koloni Anatoliko Acheleia Konia Chlorakas Empa Lempa Kisonerga Maa Tala Trimithousa Mesogi Mesa Chorio

Table B-9. Percentage of conventional dwellings for urban and rural residence based on the numbers given in Table B-1 and Table B-2

%	URBAN								RURAL							
TYPE / YEAR	Single House	Semidetached or doublex	Row houses	Backyard houses	Not stated	Apartment blocks	In a partly resid. Build.	Other	Single House	Semidetached or doublex	Row houses	Backyard houses	Not stated	Apartment blocks	In a partly resid. Build.	Other
Before 1950	45	10	28	10	0	3	5	0	55	6	36	2	0	0	0	0
1950-1959	46	20	8	13	0	5	7	0	79	7	12	1	0	0	0	0
1960-1969	39	26	2	12	0	11	8	0	82	8	7	2	0	1	0	0
1970-1979	25	19	15	5	0	24	13	0	83	7	4	3	0	2	1	0
1980-1989	25	19	8	2	0	30	15	0	69	9	5	3	0	10	4	0
1990-1992	33	21	7	2	0	27	10	0	63	8	7	2	0	17	3	0
Not stated	23	15	4	6	8	28	16	0	32	6	12	1	3	42	4	0

Note: All values are percentages

Table B-10. Percentage of conventional dwellings low rise and high rise for urban and rural residence based on the numbers given in Table B-1 and Table B-2

	URBAN		RURAL	
Year	**Low Rise**	**High Rise**	**Low Rise**	**High Rise**
Before 1950	91.61%	8.39%	98.53%	1.47%
1950-1959	86.64%	13.36%	95.58%	4.42%
1960-1969	80.20%	19.80%	96.07%	3.93%
1970-1979	63.83%	36.17%	95.80%	4.20%
1980-1989	54.48%	45.52%	85.96%	14.04%
1990-1992	62.29%	37.71%	78.74%	21.26%

3.4 KORONIDA

ASSUMPTIONS

- The record of the Department of Statistics and Research for the stone and adobe buildings starts in 1982. From that record it is apparent that after 1980 very few buildings have been built with the use of such materials. It was therefore assumed that after 1982 there were no stone or adobe buildings constructed.
- Another assumption had to be made concerning the apartment blocks. Based on the data concerning the buildings constructed in 1996 it was assumed that there are approximately 3 to 4 apartments per floor in each apartment block and that the trend, which existed in 1996, is the same for the other years.

CONCLUSIONS

TYPE (Table B-4)

The total number of residential buildings up to 1996 is 204300 of which 28948 are made of stone, 18819 are made of mud-dried bricks (adobe) and 156533 are reinforced concrete.

The majority of the buildings consist of a ground floor and 1 storey, 103039 in total. The ground floor single houses come second with 32979 and the rest follow, based on their height (i.e. 2 storey, 3 storey, 4 storey etc.).

Limassol, and Paphos have the highest of stone made buildings whereas Nicosia has the highest percentage of adobe structures. This could be attributed to the long history of the island with earthquakes. Paphos and Limassol lie in a more active seismic zone than Nicosia.

Furthermore 37% of the buildings in Paphos are stone made which explains the high vulnerability of the area to earthquakes. In general 50.4% of all the residential buildings in Cyprus consist of a ground floor and 1 storey.

AGE (Table B-3)

The age of a building is a parameter that significantly affects its vulnerability. In general it has been concluded that 65% of the stone-made buildings and 75% of the adobe are over 50 years old. Another remarkable fact is that approximately 27% of the existing building stock of the island was constructed in the 80s.

VALUE

The introduction of the aseismic code in 1992 has not increased the cost of construction. The cost of the construction of residential buildings represents 50-55% of the total construction costs in the island. The expense of construction and repair of the infrastructure was approximately £100,000,000 (one hundred million pounds CY) per year, whilst since 1993 it has increased to around £150,000,000 (one hundred and fifty million pounds CY) per year.

Bearing in mind that these expenses correspond to a limited number of works (e.g. dams, airports etc.) it can be concluded that possible damage to anyone of these structures due to an earthquake will result in very high repair or even rebuilding costs.

COST OF CONSTRUCTION (Table B-5 and Table B-6)

For the period of 1974-1982 most of the residential units constructed had a relative low cost of construction (between £5,000 to £10,000 CY) this can be mainly attributed to the high demand of cheap housing for the refugees (1974 Turkish Invasion).

As far as the cost per house and apartment for the period 90-96 the main conclusions is that houses cost more in Nicosia and less in Famagusta. The same is valid for the apartments due to the trend in Nicosia of constructing apartments that take up a whole floor (house-apartments) whereas in Famagusta most of the apartments constructed are for the tourism industry and they are small.

3.5 AUTHORS ASSUMPTIONS

In addition to the assumptions made by KORONIDA further assumptions were made by the author. Based on Table B-3 and the database of the number of housing buildings for each village & town, the following conclusions and assumptions were made:

1. The "not stated" will be divided equally to the other categories

2. After 1980 all buildings are reinforced concrete (i.e. superior construction). The percentages for houses and apartments for Urban and Rural residency for each district are given in the following table. These were calculated by taking the total of the buildings built between 1981 and 1990 (Table B-3) and then finding what percentage the RC Houses and RC Apartments take up. The same is calculated for the buildings built between 1991 and 1996. The values given in Table B-11 are the average of the two results.

Table B-11. Percentage distribution of reinforced concrete houses and apartments in all the districts after 1980

	URBAN		RURAL	
DISTRICT	***Houses***	***Apartments***	***Houses***	***Apartments***
Nicosia	73%	27%	100%	0%
Famagusta	53%	47%	100%	0%
Larnaca	64%	36%	100%	0%
Limassol	68%	32%	100%	0%
Paphos	57%	43%	100%	0%

3. Buildings in Rural areas built before the 1960s will be considered as either adobe or stone-made (i.e. standard / substandard construction).

4. Buildings in Urban areas built before 1960 will follow a specified percentage distribution. This was calculated by adding up all the buildings of all types constructed "before 1950" and between "1950 –1960" and estimating the percentage of each type. The results of these calculations for each district are presented in Table B-12.

Table B-12. Percentage Distribution of the type of construction in the urban areas before 1960

DISTRICTS	ADOBE & STONE	RC HOUSES	RC APARTMENTS
Nicosia	68.70%	26.5%	4.8%
Famagusta	70.23%	28.9%	0.9%
Larnaca	83.23%	15.5%	1.2%
Limassol	68.58%	29.0%	2.4%
Paphos	84.32%	15.4%	0.3%

5. For the rural areas it will be assumed that no reinforced concrete apartments were built between 1960–1969 and 1970–1979. In the urban areas during the same period no adobe or stone buildings were built. Both areas have reinforced concrete houses of that period. From the database of the number of buildings for each village and town it was possible to calculate the percentage of the rural houses and urban houses for each district Table B-13. Then from the data of Table B-3 the percentages of RC houses, RC apartment and adobe/stone buildings were calculated again for each district. These are presented in Table B-14.

Table B-13. Percentage of the urban houses and rural houses for each district

DISTRICTS	URBAN	RURAL
Nicosia	76.3%	23.7%
Famagusta	0%*	100%
Larnaca	63.0%	37.0%
Limassol	82.0%	18.0%
Paphos	57.2%	42.8%

*The urban areas of the Famagusta district (i.e. the town Famagusta) are occupied by the Turkish troops since 1974.

Table B-14. Percentage Distribution of the type of construction in each district between 1961 and 1979

DISTRICTS	ADOBE & STONE	RC HOUSES	RC APARTMENTS
Nicosia	1.43%	66.83%	31.74%
Famagusta	1.12%	89.08%	9.8%
Larnaca	2.24%	80.75%	17.01%
Limassol	2.82%	75.37%	21.81%
Paphos	9.29%	81.49%	9.22%

The percentages of the various types of buildings for rural and urban areas for all the districts were then estimated and are listed in Table B-15.

Table B-15. Percentage Distribution of the type of construction for rural and urban areas in each district between 1961 and 1979

DISTRICTS	URBAN			RURAL		
	ADOBE STONE	RC HOUSES	RC APARTMENT	ADOBE STONE	RC HOUSES	RC APARTMENT
Nicosia	0%	44.56%	31.74%	1.43%	22.27%	0%
Famagusta	0%	0%	0%	1.12%	89.08%	9.8%
Larnaca	0%	46.04%	17.01%	2.24%	34.71%	0%
Limassol	0%	60.10%	21.81%	2.82%	15.27%	0%
Paphos	0%	47.95%	9.22%	9.29%	33.54%	0%

The case of Famagusta is rather problematic since due to the occupation there are no data available for its current situation. This made it impossible to calculate the ratio of rural/urban houses and therefore the percentage of the type of construction for rural and urban areas in each district between 1961 and 1979. Furthermore, the fact that it has been occupied since 1974 means that no buildings have been constructed in the town during the 80s. So an assumption to resolve this problem is to assign the % found for the whole district to the rural areas. For the estimation of the different types of buildings in each village and town the following percentages Table B- 16 are going to be used. These were calculated based on the values of Table B-15 and increased to become 100%.

Table B- 16. Percentage Distribution of the type of construction for rural and urban areas in each district between 1961 and 1979

DISTRICTS	URBAN			RURAL		
	ADOBE STONE	RC HOUSES	RC APARTMENT	ADOBE STONE	RC HOUSES	RC APARTMENT
Nicosia	0%	58%	42%	6%	94%	0%
Famagusta	0%	0%	0%	1.12%	89.08%	9.8%
Larnaca	0%	73%	27%	6%	94%	0%
Limassol	0%	73%	27%	16%	84%	0%
Paphos	0%	84%	16%	22%	78%	0%

4 INVESTIGATION OF EARTHQUAKE LIFE LOSSES IN CYPRUS

4.1 THE EARTHQUAKE OF SEPTEMBER 1953

EARTHQUAKE IN CYPRUS

FORTY KILLED

1,500 HOMELESS IN TWO VILLAGES

BRITISH TROOPS' AID

From Our Correspondent

NICOSIA, SEPT. 10

Cyprus experienced its most severe earthquake for centuries soon after 6 o'clock this morning when some villages in the Paphos district, within a radius of 20 miles of Ktima, were either completely or partly wrecked. The number of killed is put at about 40, and about 100 seriously injured are being treated at Limassol hospital.

The most seriously damaged villages are Stroumbi and Kidassi, where virtually no houses are left standing and some 1,500 people are homeless. The shock was also felt in Nicosia and other towns of Cyprus, but caused no injuries or damage, though houses trembled and furniture rattled, making alarmed citizens rush into the streets in pyjamas and dressing gowns.

IMMEDIATE AID

As soon as news reached Nicosia of the disaster in the Paphos area, the Government took steps to send help in the shape of tents, blankets, olives, cheese, and bread for distribution to the victims, while doctors, ambulances, and extra police hastened to the scene to treat the injured. The Army and Royal Air Force are also aiding in every way. A detachment of Royal Engineers are helping to rescue those trapped in the débris and to demolish unsafe buildings.

The district affected is a wine producing one, with village populations ranging from 700 to 200. Most of the houses are made of sun-dried mud bricks with wattle roofs. It was fortunate that the earth tremors, which lasted about 15 seconds, occurred just after 6 o'clock, because villagers at that time were mostly in the vineyards and fields picking grapes and had their children with them, before going to school which opens at 8 o'clock. Luckily, also, no fires broke out.

VILLAGERS' ACCOUNT

Villagers all have the same tale to tell. Suddenly they felt the earth tremble beneath their feet and were thrown to the ground while village buildings, the church, the school, and houses either collapsed in clouds of dust or showed great cracks in the walls while the roofs caved in. When the shocks subsided villagers frantically tore at their wrecked homes, trying to rescue anyone inside or to save valued pieces of furniture. Many, fearing further shocks, left the villages and made for the towns, but most are sitting in open spaces, surrounded with what belongings they managed to save, discussing their "day of horror" and mourning fellow villagers who were killed. These include some girls and young children.

In Paphos itself, a town of about 6,000 inhabitants, some 200 houses were damaged badly and six people were killed. To-night the whole of Paphos is sleeping out in the open, while convoys of food and equipment are making their way to the stricken area from Nicosia and Famagusta. The distribution of bread and olives has been begun at Stroumbi and Kidassi and a Red Cross team is operating in Stroumbi.

Figure B- 16. A. **Extracts from "The Times" Friday, September 11th 1953;**
B. **Photos from the archives of the Press Information Office (PIO) of Cyprus**

10th September 1953

The earthquake occurred at 6:00 am, in September, 35km offshore from the southwest coast of Cyprus. According to Havouzari (1983) at that period the population density, of the Paphos District was 42 persons per square kilometre. Therefore, it is apparent that the area was not densely populated.

The district of Paphos is a wine producing area and in September the grapes have to be picked and when the earthquake struck the majority of the villagers were either in the vineyards picking grapes or in the fields working. The children were helping their parents before going to school. Had this event occurred in a more densely populated area, or earlier in the night when everybody was at home asleep, or perhaps later in the day when the children were at school, the number of fatalities and injuries would have been much higher. However, if the event occurred in a more developed area with better quality of construction (at that time the western part of Cyprus was the least developed) perhaps the fatalities and injuries could have been avoided. On the other hand, if the event occurred inland taking into account the small size of the island the devastation would have been total.

4.2 LETHALITY RATIO

M1: POPULATION PER BUILDING

The population per building varies greatly from one place to another and can change dramatically in an area in a short period of time. In residential building stock the P/B is equivalent to the average family size living in each house. In Europe this is approximately 2 to 3 whereas Iran, Turkey etc. it is 8 (16 person households not uncommon). P/B is a major variable in determining the number of people at risk in a building collapse and is established as the potential mortality for a building type Figure B-17.

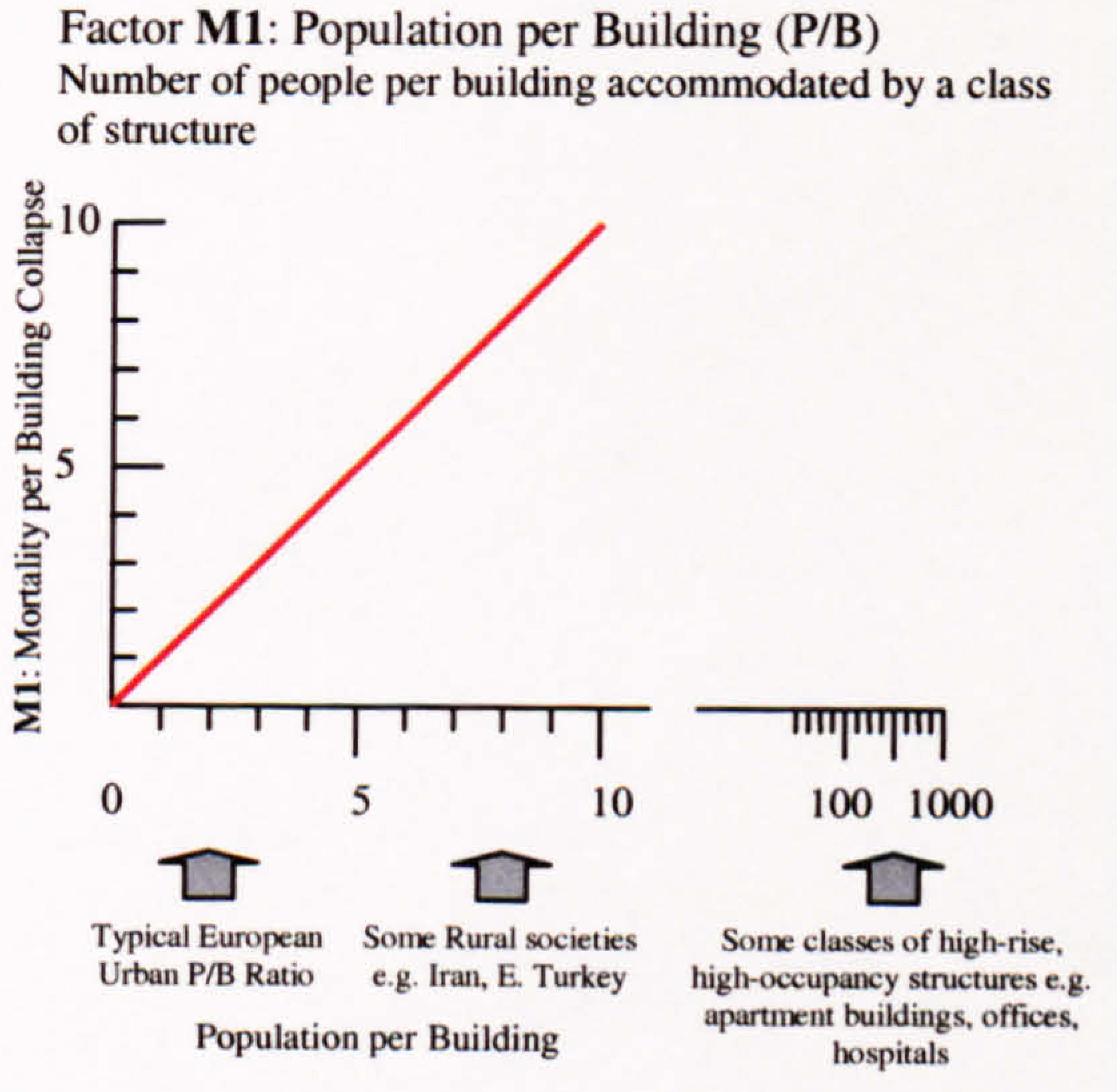


Figure B-17. M1 – Population per Building (after Coburn and Spence, 1992)

M2: OCCUPANCY AT TIME OF EARTHQUAKE

The number of people killed during an earthquake depends also on the time of the day the earthquake will strike (Figure B-18). Rural areas would be affected more during a night earthquake since during the day most occupants will be outdoors. In Urban areas on the other hand where people move from one building to another (from residential to non-residential and vice versa) it will all depend on the vulnerability of the particular building. Furthermore, the season (winter or summer) in which the earthquake occurs also affects the number of fatalities (i.e. summer holiday resort - summer holidays – increase of population – higher death toll).

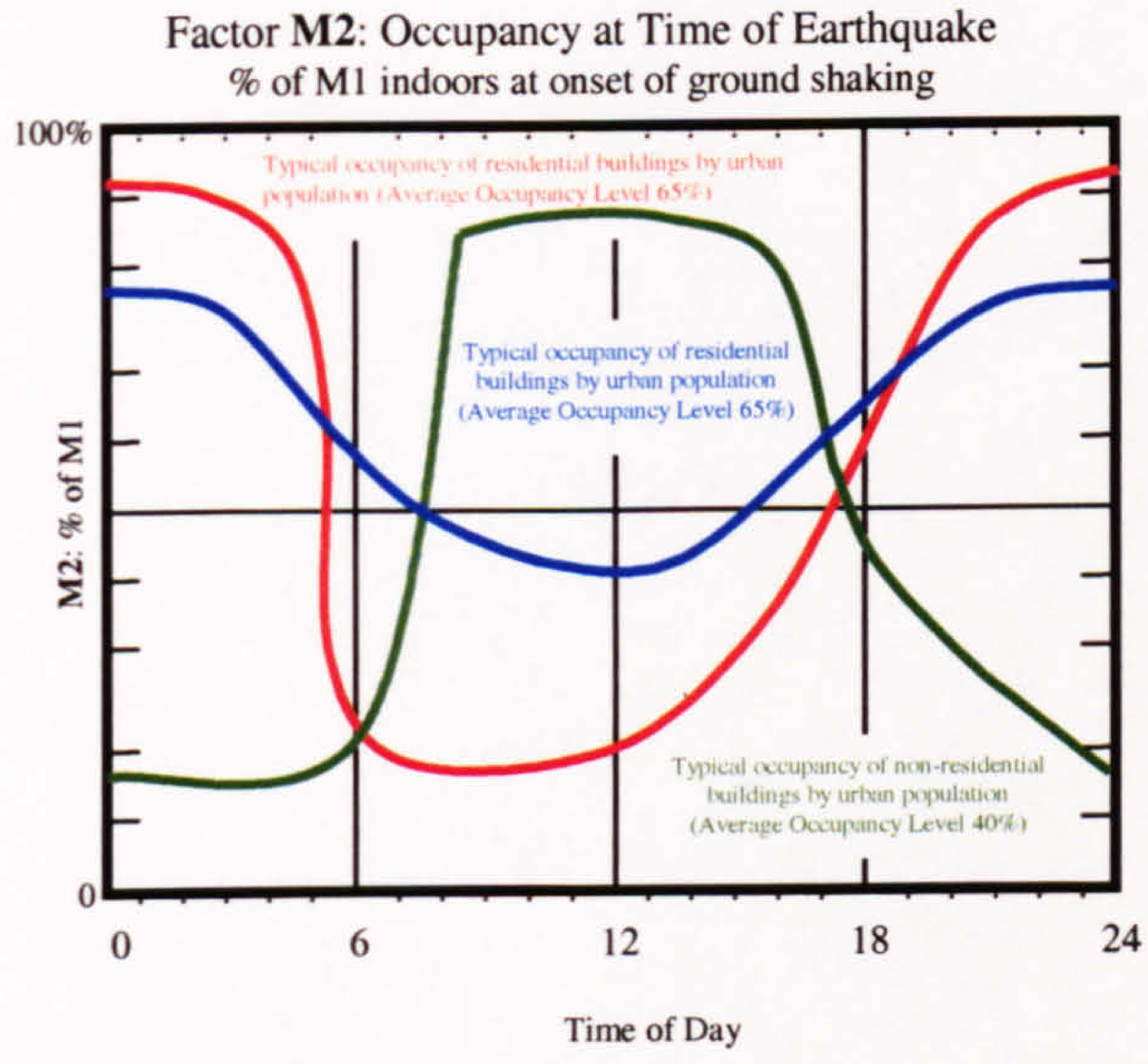


Figure B-18. M2 – Occupancy at time of earthquake (after Coburn and Spence, 1992)

M3: OCCUPANTS TRAPPED BY COLLAPSE

It is generally accepted and proven from experience that during an earthquake, if a building collapses not all the people that are inside would be trapped. Depending on the individuals and also the type of the building (i.e. single storey or multi-storey) it is possible for people to escape before the building collapse, or the collapse may not be total, or even free themselves relatively easily.

According to Coburn and Spence (1992) in general the fewer the storeys in a building the more chances the occupants have to escape before it collapses or to free themselves after the collapse. However, this does not include weak masonry buildings in the epicentre of strong earthquakes or similar cases were the collapse is immediate.

Table B-17 and Figure B-19 present the estimated average percentage of occupants trapped by collapse. This entrapment rate can be reasonably assessed by equating the M3 value to the volumetric reduction of the building in collapse.

Table B-17. M3: estimated average percentage of occupants trapped by collapse (Coburn and Spence, 1992)

Type of Building	MSK Intensity			
	VII	VIII	IX	X
COLLAPSED MASONRY BUILDINGS (UP TO 3 STOREYS)				
	5%	30%	60%	70%
COLLAPSED RC BUILDINGS (3 – 5 STOREYS)				
Near Field, high-frequency ground motion:				70%
Distant, long-period ground motion:				50%

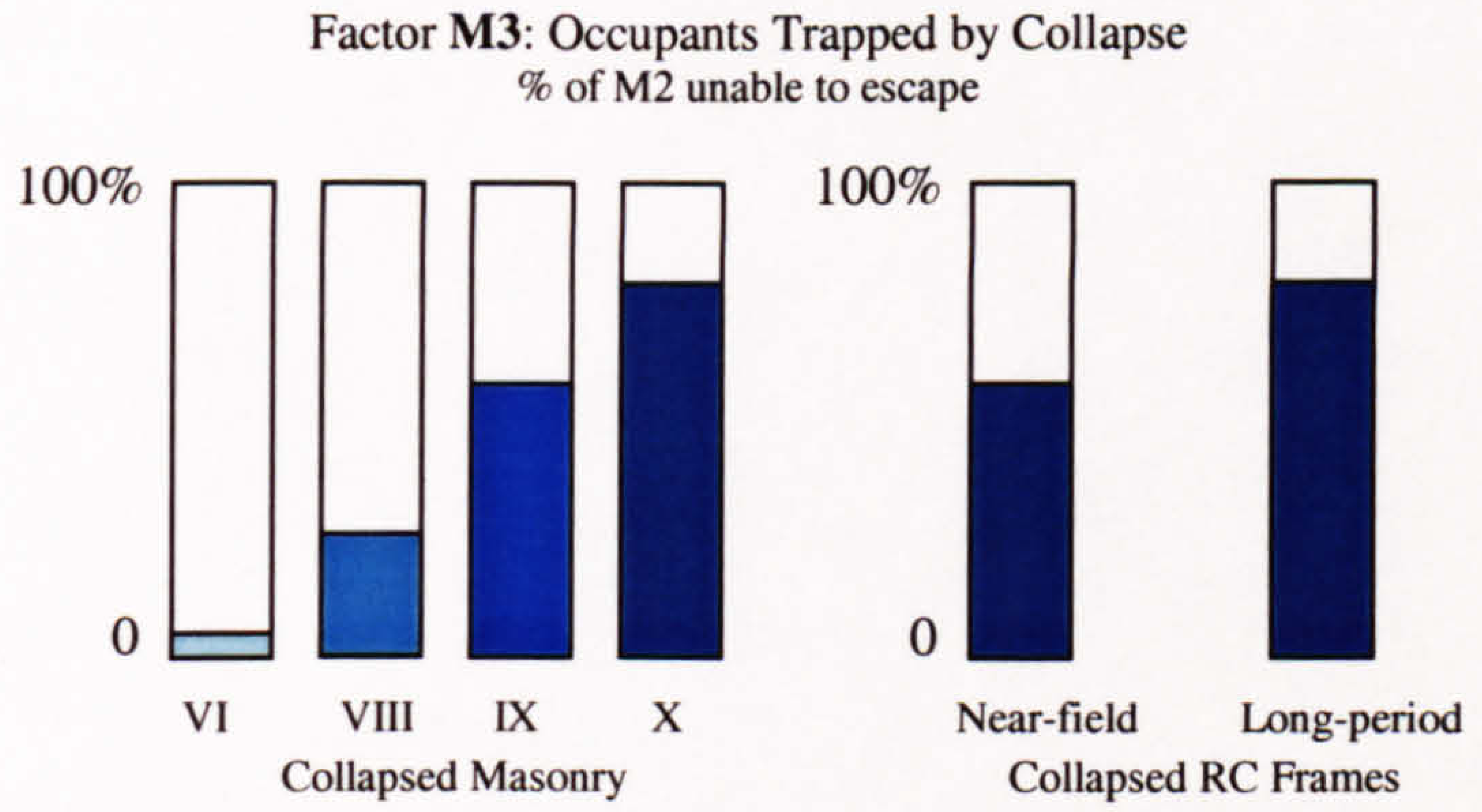


Figure B-19. M3 – Occupants trapped by collapse (after Coburn and Spence, 1992)

M4: INJURY DISTRIBUTION AT COLLAPSE (T_0)

The injuries sustained by people caught in building collapses are of a wide range and of various degrees. Some occupants are killed immediately when the collapse occurs and others sustain injuries of various degrees. According to Coburn and Spence (1992) the M4 factor in the casualty model is the proportion of the immediate collapse fatalities. Table B-18 and Figure B-20 present one of the simplest and most useful to emergency managers, injury severity scales (ISS) proposed for quantifying earthquake epidemiological studies (Coburn and Spence, 1992). It is based on a four-point standard triage classification of injuries.

Table B-18. M4: estimated injury distributions at collapse (% of trapped occupants)

Triage	Injury Category	Masonry	RC
1	Dead or unsaveable	20%	40%
2	Life threatening cases needing immediate medical attention	30%	10%
3	Injury requiring hospital treatment	30%	40%
4	Light injury not necessitating hospitalisation	20%	10%

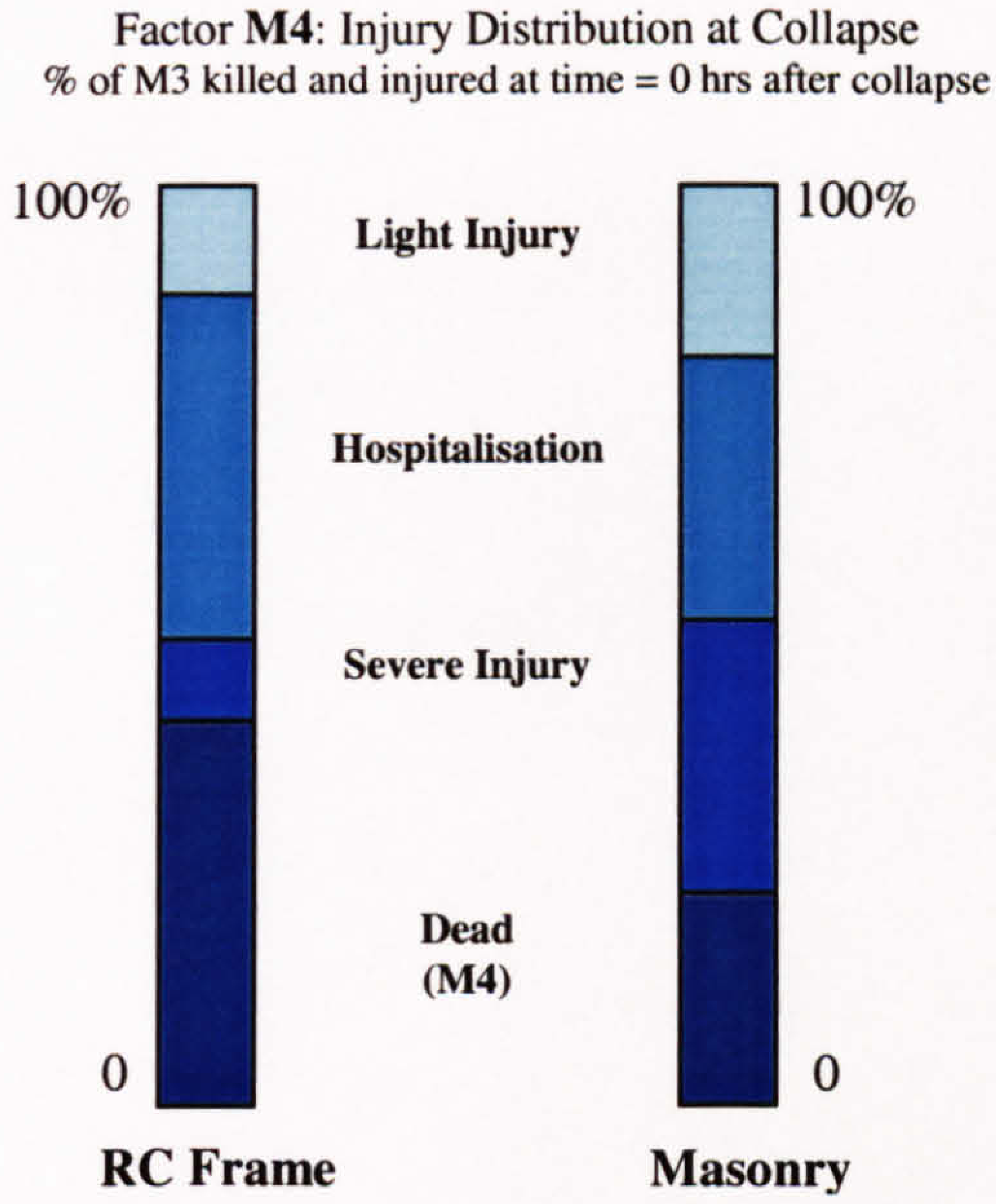


Figure B-20. M4 – Injury distribution at collapse (after Coburn and Spence, 1992)

The M4 factor is mainly affected by the void-to–volume ratio of the collapsed rubble and the size of the cavities left within it. Some of the other parameters that could also affect the M4 factor are:

- the mass of the building type,
- the fragment size of the collapsed elements,
- the dust-producing potential of the building materials and finishes,
- the design of stairways,
- the circulation routes etc.

M5: MORTALITY POST – COLLAPSE

It is obvious that the people trapped in the rubble after a structural collapse will eventually die if they are not rescued and given medical treatment if needed. Also the ones with severe injuries will perish at a faster rate (fade-away time) than those who are not seriously hurt. In cases of collapsed buildings the time is of extreme importance. With every hour that passes death rates increase.

The preparedness and rescue effectiveness of the people not hurt by the earthquake, who will essentially be the initial rescuers until the proper rescue teams arrive, will consequently affect and increase the number of people rescued, who would have otherwise perished. It is estimated that the 90% of the victims rescued from collapsed buildings, are pulled quickly from the ruins by regular people present in the area during the earthquake (Krimgold, 1987 in Coburn and Spence, 1992).

The M5 factor depends on the effectiveness of the post-collapse rescue activities (Table B-19 and Figure B-21). Therefore, in cases of excessive devastation where a large majority of the population is affected (i.e. either killed or seriously injured) and there are not any people present to act as the initial rescue teams, this factor increases dramatically.

Some of the factors that influence the effectiveness of the search and rescue procedures and therefore the rescue rates of victims are the manpower, equipment, search techniques and transport resources. Further factors, which affect the fade-away time (perish rate of trapped victims) and consequently the M5, include the weather conditions in general and in particular the temperature and rainfall. The possible aftershocks and fire outbreaks are also affecting the perish rate of the trapped victims. Moreover these last two hazards can produce further entrapments, fatalities and injuries.

Table B-19. M5: percentage of trapped survivors in collapsed buildings that subsequently die (Coburn and Spence, 1992)

Situation	Masonry	RC
Community incapacitated by high casualty rate	95%	-
Community capable of organising rescue activities	60%	90%
Community + emergency squads after 12 hours	50%	80%
Community + emergency squads + SAR (search and rescue) experts after 36 hours	45%	70%

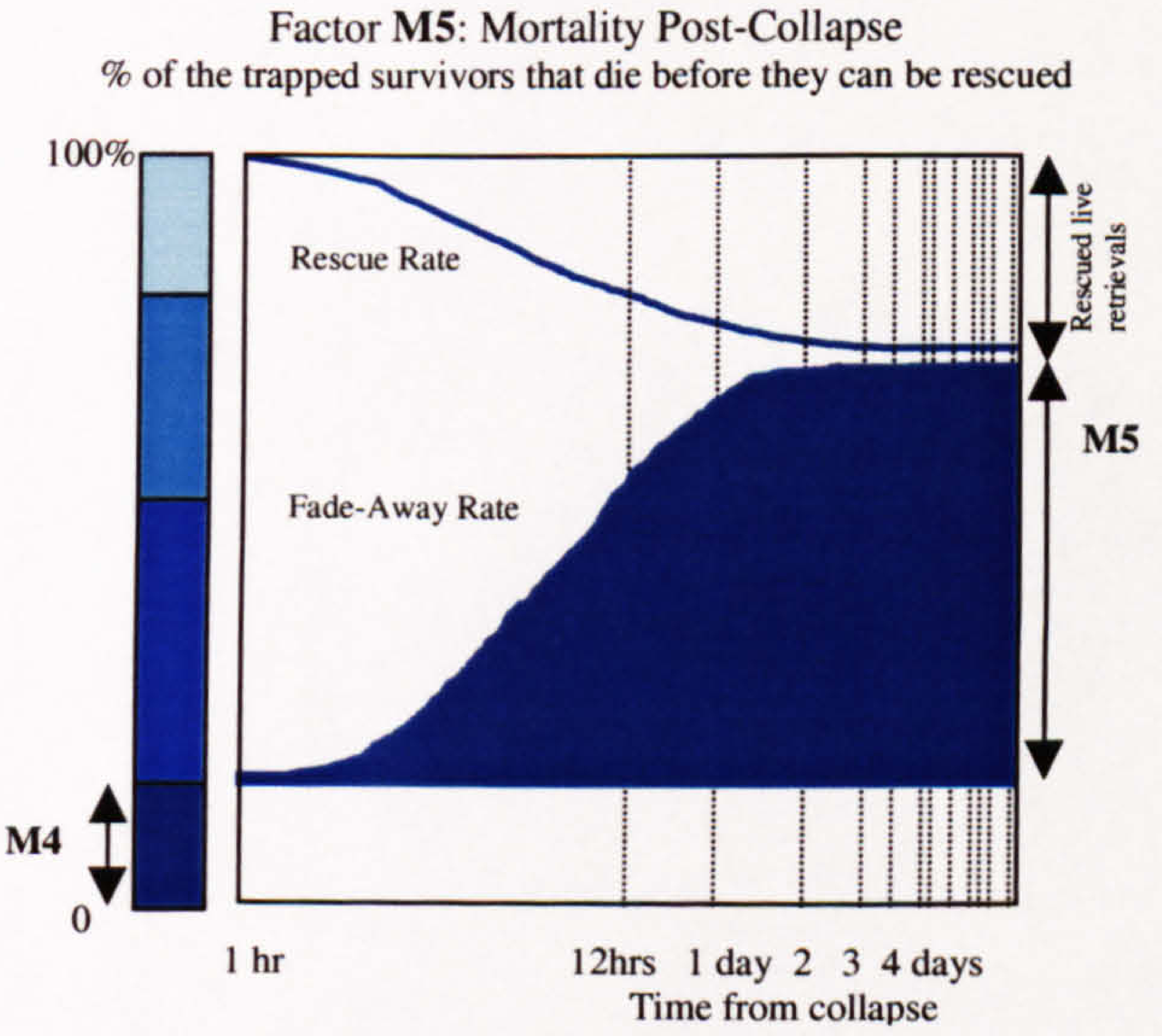


Figure B-21. M5 – Mortality post - collapse (after Coburn and Spence, 1992)

APPENDIX C

Further on the Model Modification/Improvements/Validation

FURTHER ON THE MODEL MODIFICATIONS/IMPROVEMENTS/VALIDATION

This appendix provides further data on the model modification, improvements, and validation, in support of the work presented in chapter 4.

1 LIMITING THE CATALOGUE

Calculations for the estimation of the value of magnitude required for an intensity VI to be experienced at the epicentre.

Based on the Modified Mercalli Intensity (MMI) scale structural damage begins with intensity VI. In an attempt to identify a magnitude value which would the attenuation equations derived by Theodulidis and Papazachos (1992) were used.

So:

$$\ln(\alpha) = 0.28 + 0.67\,\mathrm{Im}\,m + 0.42S$$
$$= 0.28 + 0.67 \times 6$$
$$= 0.28 + 4.02$$
$$= 4.3$$

for shallow earthquakes at alluvial site (i.e. S=0) with R=0

$$\ln(\alpha) = 3.88 + 1.12M_S - 1.65\ln(R+15) + 0.41S$$
$$4.3 - 3.88 = 1.12M_S - 1.65\ln 15$$
$$\frac{4.3 - 3.88 + 1.65\ln 15}{1.12} = M_S$$
$$M_S = 4.36 \approx 4.4$$

For Rock site (i.e. S=1) $M_S = 3.99$

for intermediate earthquakes at alluvial site (i.e. S=0) with R=0 and h=36

$$R_{CER} = \sqrt{R^2 + h^2}$$

$$\ln(\alpha) = 3.47 + 0.75M_W - 0.58\ln R_{CER} + 0.27S$$
$$\frac{4.3 - 3.47 + 0.85\ln(36)}{0.75} = M_W$$
$$M_W = 5.167 \approx 5.2$$

For Rock site (i.e. S=1) $M_W = 4.8$

$$M_W = 0.56M_S + 2.66$$
$$\frac{5.2 - 2.66}{0.56} = M_S$$
$$M_S = 4.5$$

For Rock site (i.e. S=1) $M_S = 3.82$

The limiting magnitude for the earthquake catalogue will be $M_S = 4.5$

2 MEAN DAMAGE RATIOS – MDR

Table C-1. Mean Damage Ratios (MDR) for a more accurate estimation of the predicted damaged buildings

Intensity	Superior			Standard
	< 4 storeys	> 4 storeys	Halls	Substandard
5	-	-	0	0
5.1	-	-	0.001	0.006
5.2	-	-	0.002	0.012
5.3	-	-	0.003	0.018
5.4	-	-	0.004	0.024
5.5	-	-	0.005	0.03
5.6	-	-	0.006	0.036
5.7	-	-	0.007	0.042
5.8	-	-	0.008	0.048
5.9	-	-	0.009	0.054
6	**0**	**0**	**0.01**	**0.06**
6.1	0.005	0.003	0.013	0.066
6.2	0.01	0.006	0.016	0.072
6.3	0.015	0.009	0.019	0.078
6.4	0.02	0.012	0.022	0.084
6.5	0.025	0.015	0.025	0.09
6.6	0.03	0.018	0.028	0.096
6.7	0.035	0.021	0.031	0.102
6.8	0.04	0.024	0.034	0.108
6.9	0.045	0.027	0.037	0.114
7	**0.05**	**0.03**	**0.04**	**0.12**
7.1	0.056	0.034	0.048	0.132
7.2	0.062	0.038	0.056	0.144
7.3	0.068	0.042	0.064	0.156
7.4	0.074	0.046	0.072	0.168
7.5	0.08	0.05	0.08	0.18
7.6	0.086	0.054	0.088	0.192
7.7	0.092	0.058	0.096	0.204
7.8	0.098	0.062	0.104	0.216
7.9	0.104	0.066	0.112	0.228
8	**0.11**	**0.07**	**0.12**	**0.24**
8.1	0.124	0.079	0.138	0.264
8.2	0.138	0.088	0.156	0.288
8.3	0.152	0.097	0.174	0.312
8.4	0.166	0.106	0.192	0.336
8.5	0.18	0.115	0.21	0.36
8.6	0.194	0.124	0.228	0.384
8.7	0.208	0.133	0.246	0.408
8.8	0.222	0.142	0.264	0.432
8.9	0.236	0.151	0.282	0.456
9	**0.25**	**0.16**	**0.3**	**0.48**
9.1	0.265	0.173	0.33	0.512
9.2	0.28	0.186	0.36	0.544
9.3	0.295	0.199	0.39	0.576
9.4	0.31	0.212	0.42	0.608
9.5	0.325	0.225	0.45	0.64
9.6	0.34	0.238	0.48	0.672
9.7	0.355	0.251	0.51	0.704
9.8	0.37	0.264	0.54	0.736
9.9	0.385	0.277	0.57	0.768
10	**0.4**	**0.29**	**0.6**	**0.8**

3 DAMAGE ASSESSMENT

According to the real data. The cost of the 1995 earthquake was £3800000 for a total of 3900 damage applications. $\text{£}3800000/3900 = \text{£}974.359 \approx \text{£}1000$

With approximately £1000 per application and assuming that a house would cost approximately £40000, it is possible to estimate what is the number of houses that suffered complete damage. $\text{£}1000/\text{£}40000 = 0.025$ $0.025 * 3900 = 97.5 \approx 100$

3.1 CASE ONE

- All the adobe and stone buildings will be considered as standard or substandard construction.
- All RC until 1979 will get the % of the > 4 storeys (i.e. worse case scenario)
- All the RC structures after 1980 will be considered as superior and will get the appropriate % depending whether they are < 4 storeys or > 4 storeys.

Table C-2. Percentage Distribution of the standard/substandard and superior construction for each of the three building types (adobe/stone, RC Houses and RC Apartments) in each period.

	Adobe / Stone		RC Houses		RC Apartments	
Period	Standard Substandard	Superior	Standard Substandard	Superior	Standard Substandard	Superior
Up to 1950	100%	-	100%	-	100%	-
50-60	100%	-	100%	-	100%	-
60-70	100%	-	100%	-	100%	-
70-80	100%	-	100%	-	100%	-
80-90	-	-	-	100%	-	100%
90-00	-	-	-	100%	-	100%

Table C-3. Mean Damage Ratios (MDR) for Cyprus (Schnabel, 1987)

	SUPERIOR CONSTRUCTION					STANDARD / SUBSTANDARD CONSTRUCTION				
	INTENSITY									
Type of Construction	VI	VII	VIII	IX	X	VI	VII	VIII	IX	X
Buildings < 4 storeys	0%	5%	11%	25%	40%	8%	17%	36%	75%	100%
Buildings > 4 storeys	5%	7.5%	14%	32%	58%					
Industrial Halls	1%	4%	12%	30%	60%					
Factors to be applied on MDR building / hall	0.2	0.25	0.33	0.50	0.67					

Based on these assumptions the total number of damaged buildings is ***1377*** with 100% damage.

$1377 / 97.5 = 14.12 \approx 14$ ***times more damaged buildings than in reality***

3.2 CASE TWO

A more realistic representation of the standard/substandard and superior construction for the various decades and the three different types of buildings was chosen and presented in Table C-4. This was decided in an attempt to reduce the number of the predicted damaged buildings which is too high compared to the number estimated of real damaged buildings of around 100. Figure C-1 presents the spatial distribution of the estimated damages.

Table C-4. Percentage Distribution of the standard/substandard and superior construction for each of the three building types (adobe/stone, RC Houses and RC Apartments) in each period.

	Adobe / Stone		RC Houses		RC Apartments	
Period	Standard Substandard	Superior	Standard Substandard	Superior	Standard Substandard	Superior
> 1950	100%	0%	80%	20%	50%	50%
50-60	80%	20%	60%	40%	40%	60%
60-70	60%	40%	50%	50%	30%	70%
70-80	40%	60%	40%	60%	35%	65%
80-90	-	-	10%	90%	10%	90%
90-00	-	-	0%	100%	0%	100%

With these numbers the results were improved significantly and the predicted damaged buildings with 100% damage came down to ***490***.

$$490/97.5 = 5.025 \approx 5 \textit{ times more damaged buildings than in reality}$$

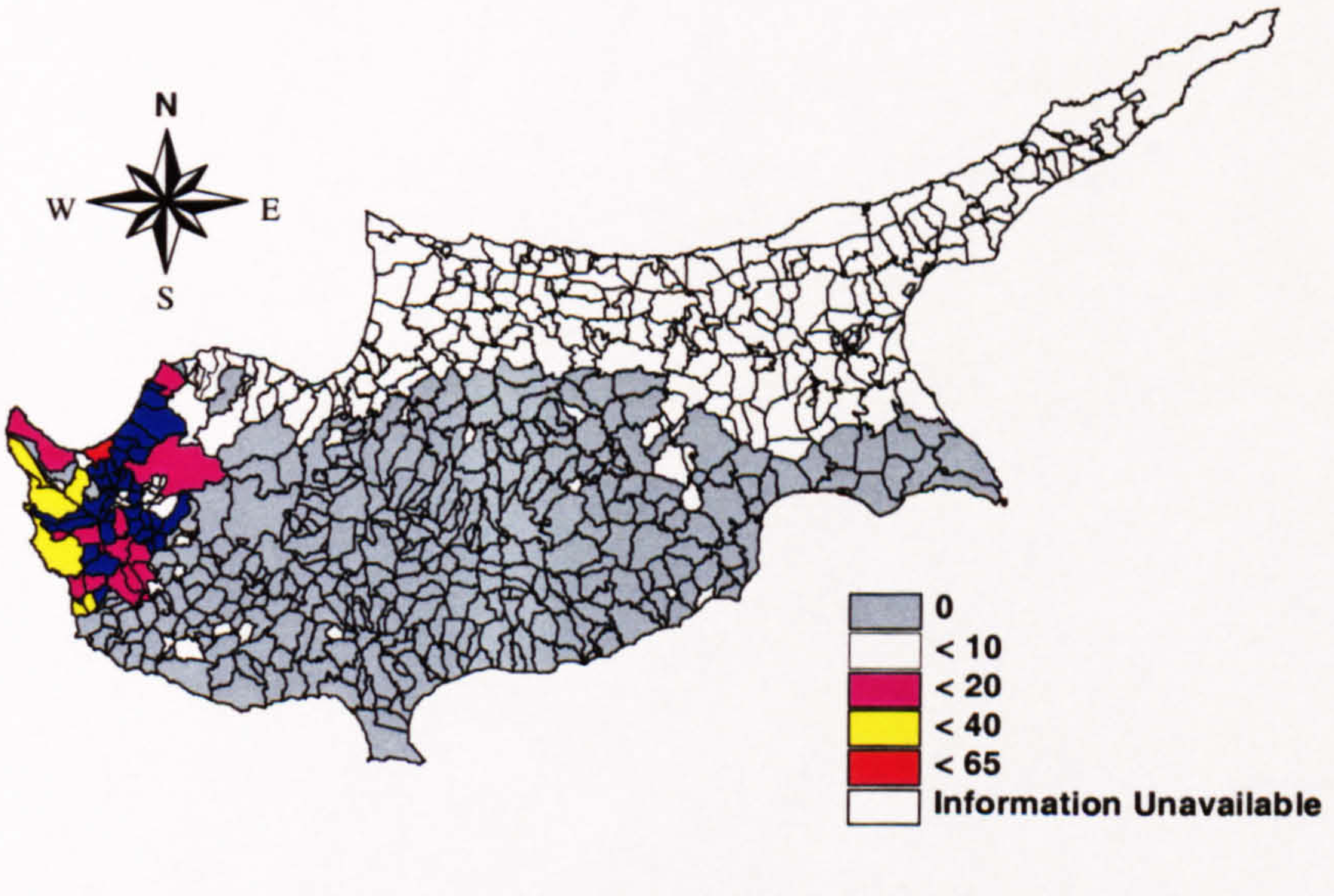


Figure C-1. Case 2 Predicted 100% damaged buildings equalled 490

3.3 CASE THREE

In an attempt to reduce the predicted damaged buildings and due to the fact that it is believed that the mean damage ratios are rather high for the existing building stock of Cyprus, it was decided to change the mean damage ratios to correspond to one degree of Intensity more Table C-5. The results obtained reduced the predicted damaged buildings from ***490*** to ***50***. This reduction is too high compared to the estimated real damaged buildings of around 100. Figure C-2 presents the spatial distribution of the estimated damages.

Table C-5. Mean Damage Ratios (MDR)

		SUPERIOR CONSTRUCTION					STANDARD / SUBSTANDARD CONSTRUCTION				
						INTENSITY					
Type of Construction		**VII**	**VIII**	**IX**	**X**	**XI**	**VII**	**VIII**	**IX**	**X**	**XI**
Buildings	**< 4 storeys**	0%	5%	11%	25%	40%	8%	17%	36%	75%	100%
	> 4 storeys	5%	7.5%	14%	32%	58%					
Industrial Halls		1%	4%	12%	30%	60%					
Factors to be applied on MDR building / hall		0.2	0.25	0.33	0.50	0.67					

$50/97.5 = 0.5128 \approx 0.5$ ***times less damaged buildings than in reality***

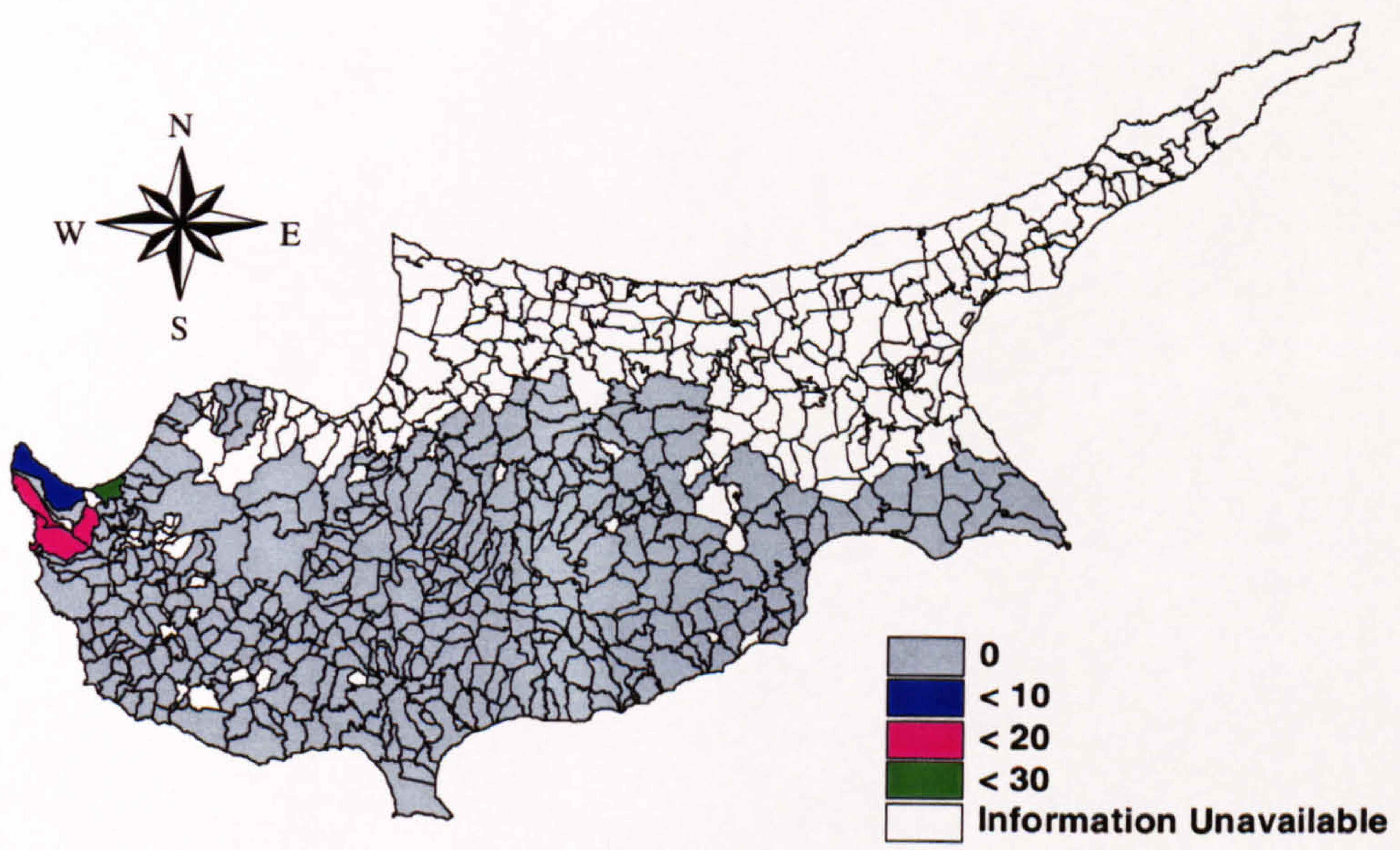


Figure C-2. Case 3 Predicted 100% damaged buildings equalled 50

3.4 CASE FOUR

Table C-3 shows the mean damage ratios for < 4 storeys to be lower than the > 4 storeys buildings. This suggests that the < 4 storeys buildings have a better vulnerability than the > 4 storeys. By examining the building stock in Cyprus since 1987, when this table was created, it can be seen that the quality of construction has been improved significantly. Furthermore, better and more experienced engineers and contractors are involved in the construction of high rise buildings than for the construction of normal houses, which leads to the conclusion that these ratios can not be the most appropriate ones and require further adjustments.

The following adjustments to the mean damage ratios for the > 4 storeys buildings were necessary (Table C-6). Figure C-3 presents the spatial distribution of the estimated damages.

Table C-6. Mean Damage Ratios (MDR)

		SUPERIOR CONSTRUCTION					STANDARD / SUBSTANDARD CONSTRUCTION				
		INTENSITY									
Type of Construction		VI	VII	VIII	IX	X	VI	VII	VIII	IX	X
Buildings	< 4 storeys	0%	5%	11%	25%	40%	6%	12%	24%	48%	80%
	> 4 storeys	0%	3%	7%	16%	29%					
Industrial Halls		1%	4%	12%	30%	60%					
Factors to be applied on MDR building / hall		0.2	0.25	0.33	0.50	0.67					

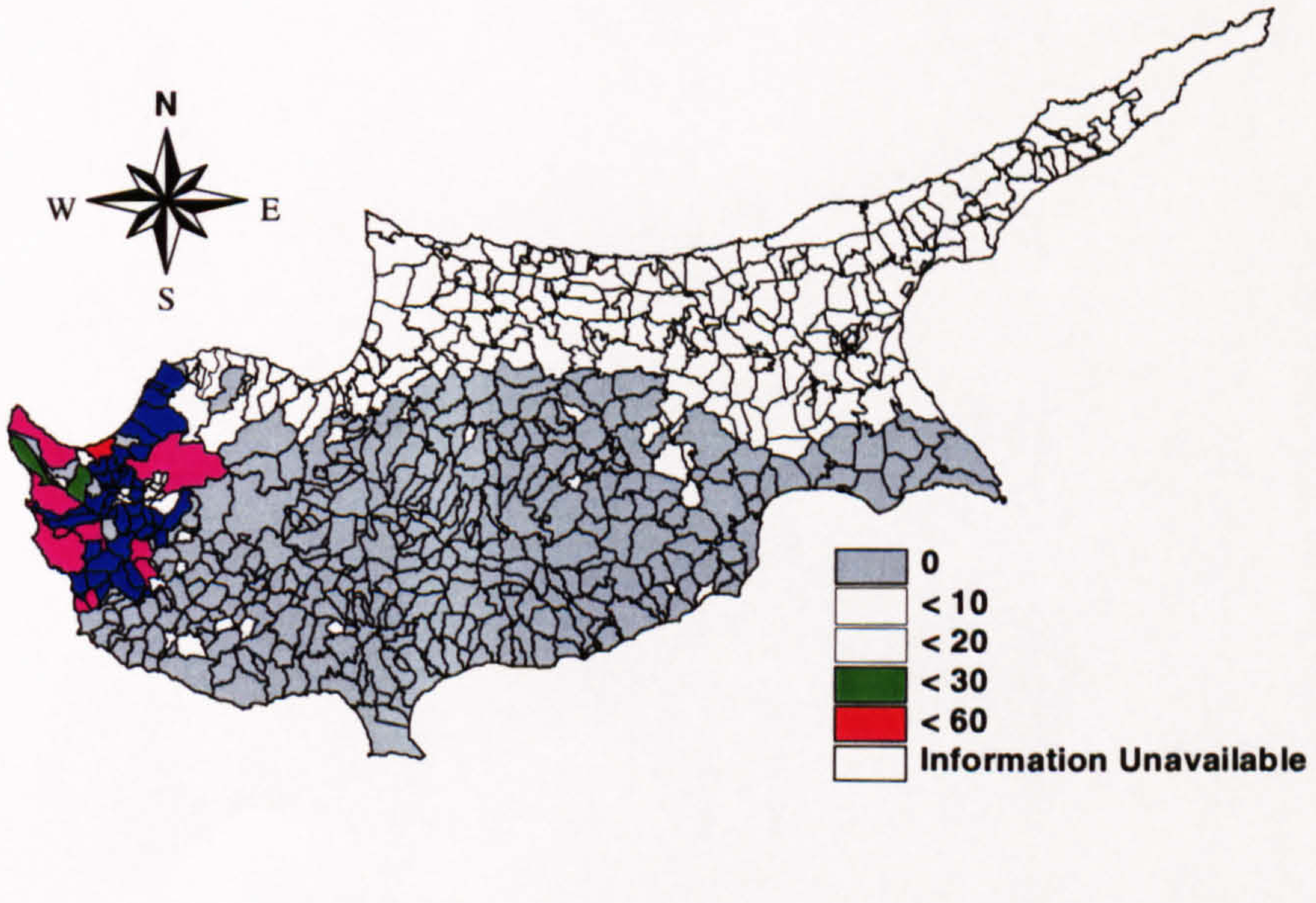


Figure C-3. Case 4 Predicted 100% damaged buildings equalled 343

APPENDIX D

Additional Results of the Parametric Studies

ADDITIONAL RESULTS OF THE PARAMETRIC STUDIES

This appendix provides additional results of the parametric studies in support of work in chapter 5.

1 EPICENTRE

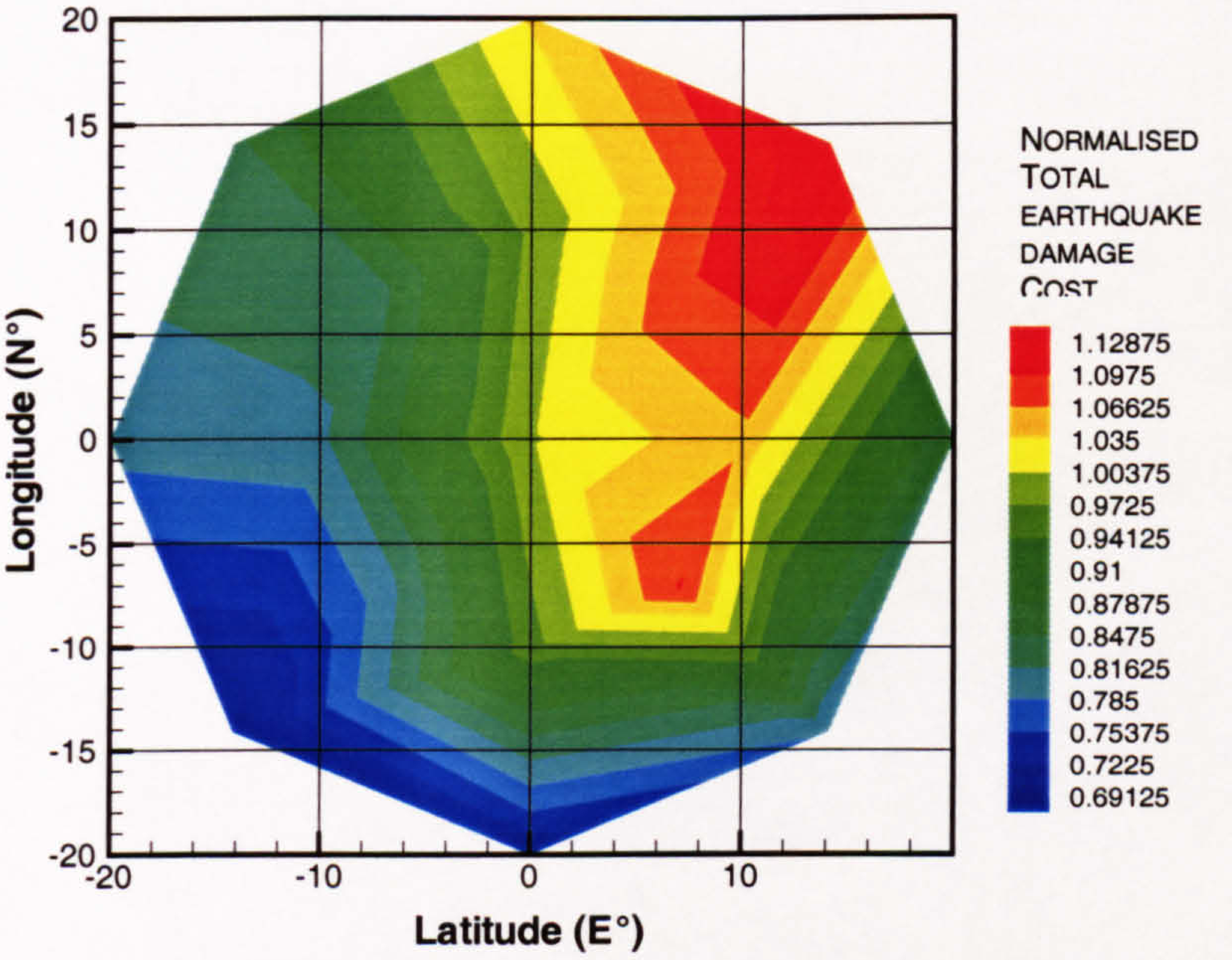


Figure D-1. Spatial distribution of the variations in the normalised total earthquake damage cost

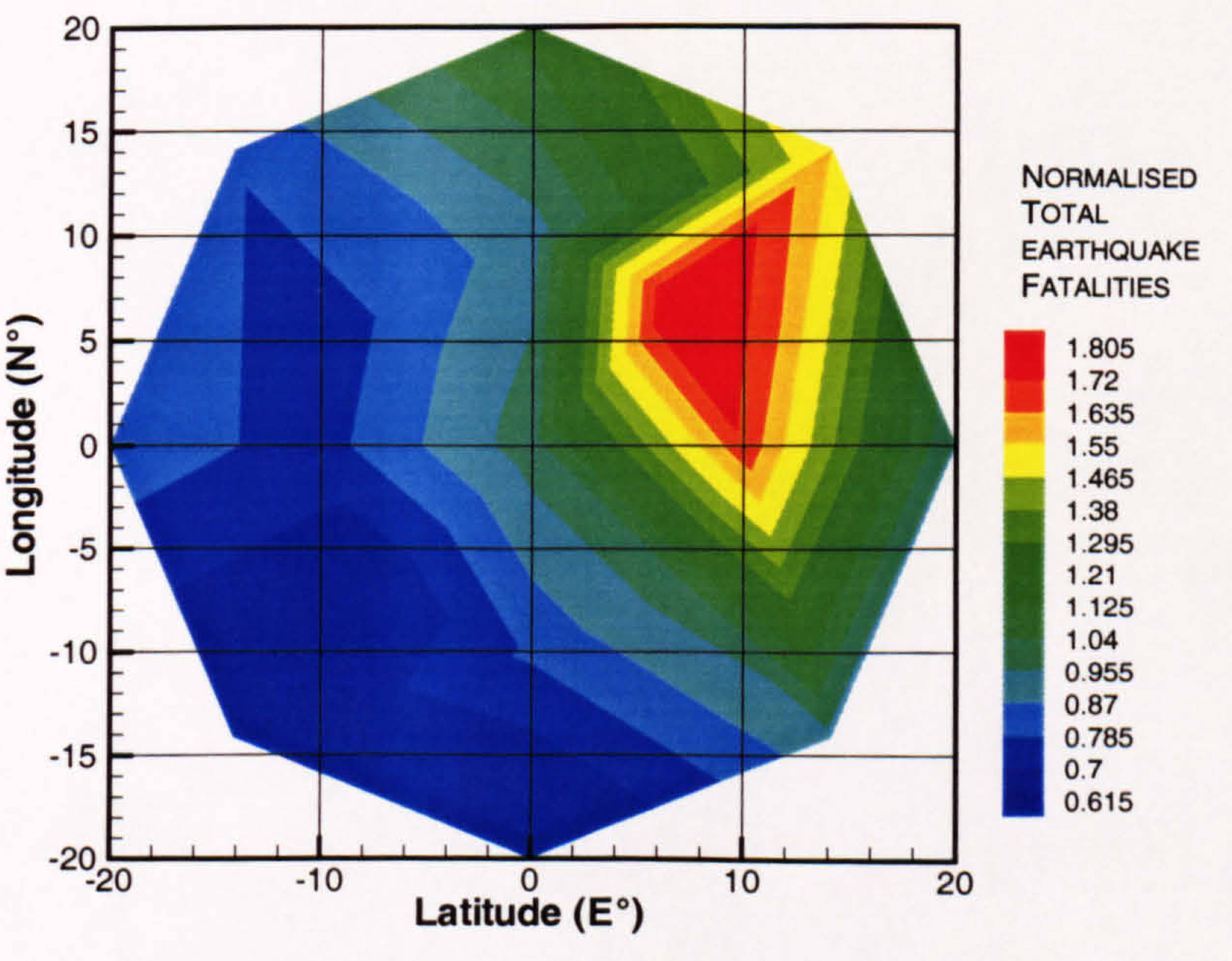


Figure D-2. Spatial distribution of the variations in the normalised total earthquake fatalities

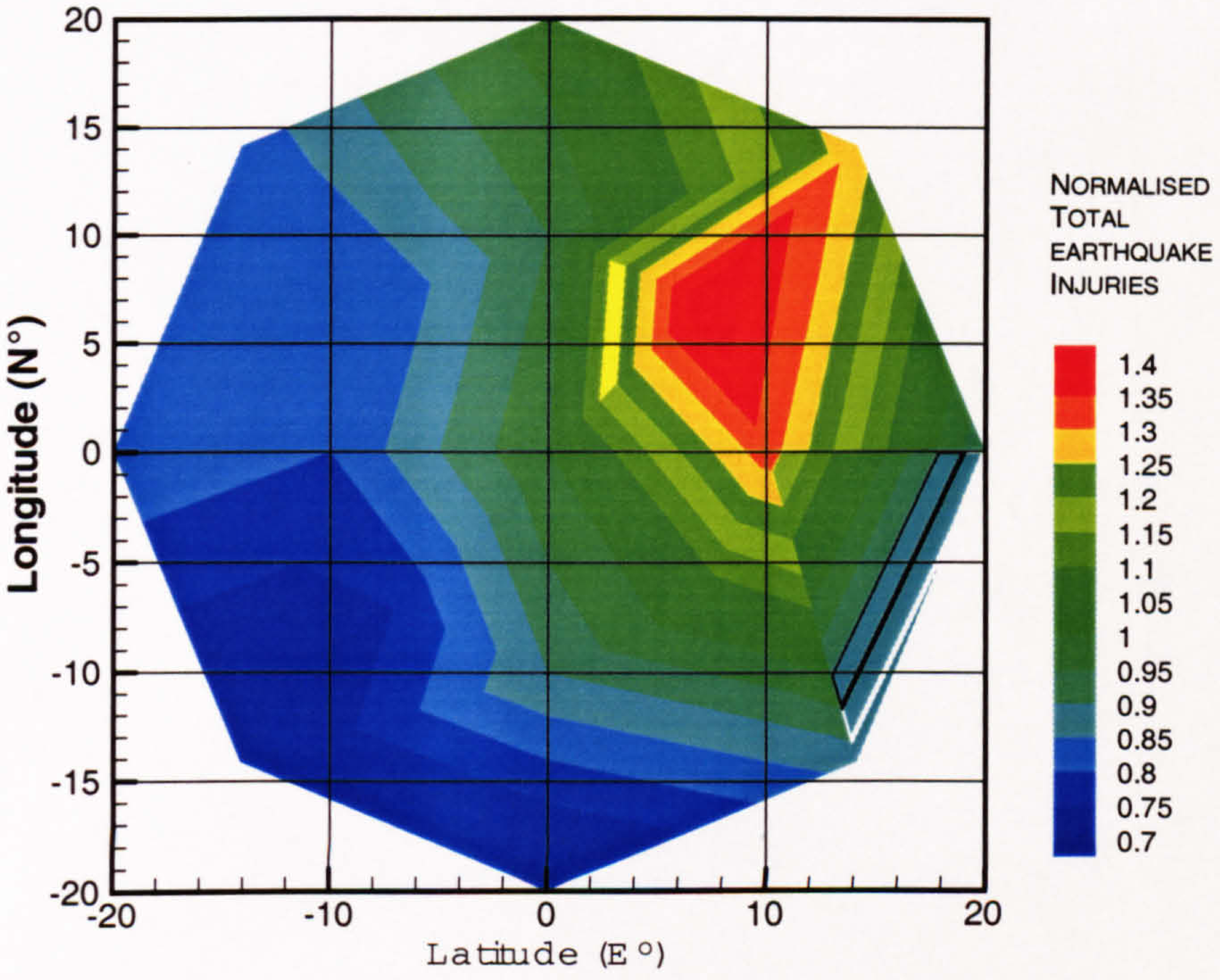


Figure D-3. Spatial distribution of the variations in the normalised total earthquake injuries

2 DEPTH

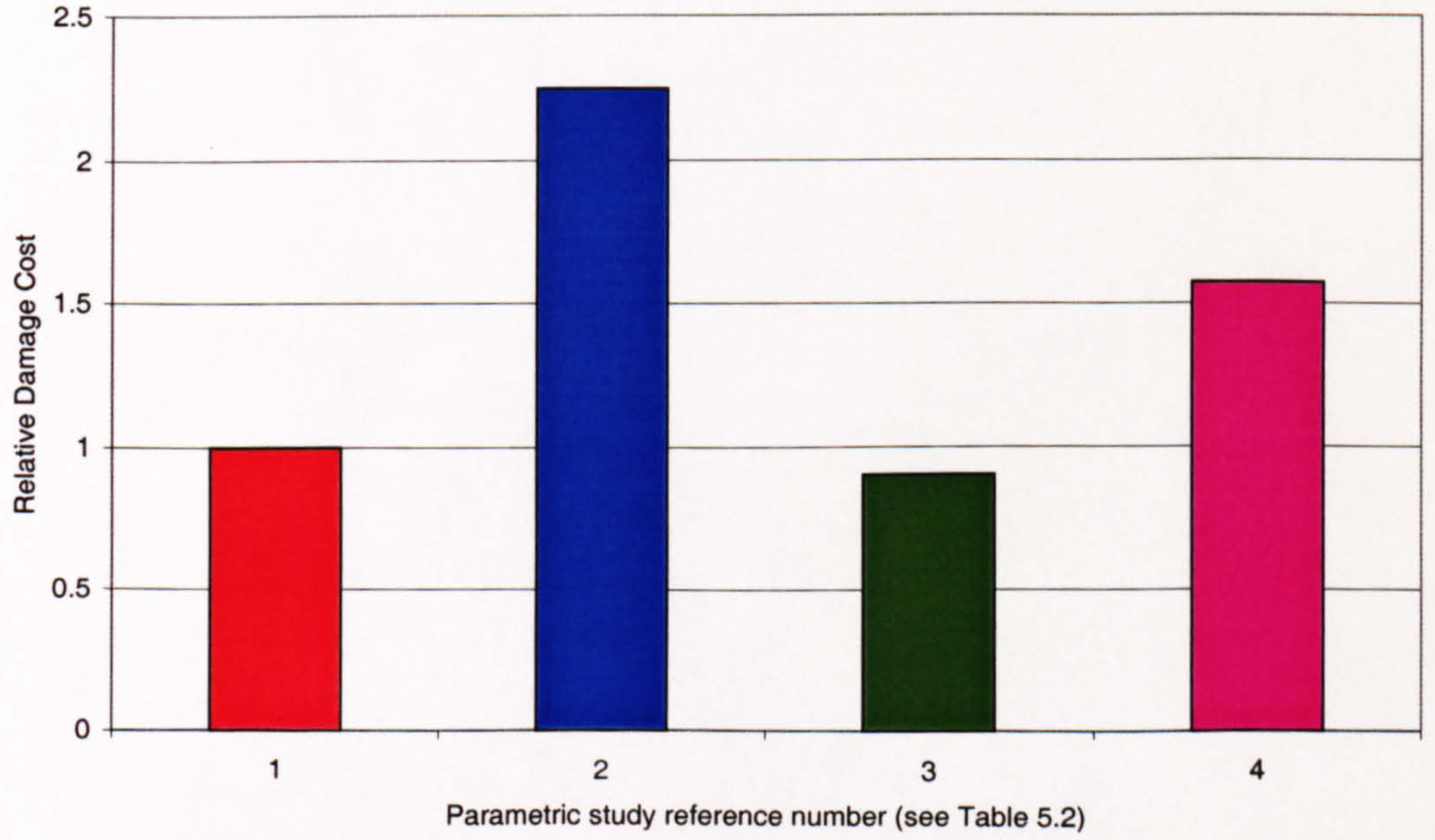


Figure D-4. Comparison of the normalised total damage costs results obtained from the parametric studies for the earthquake depth

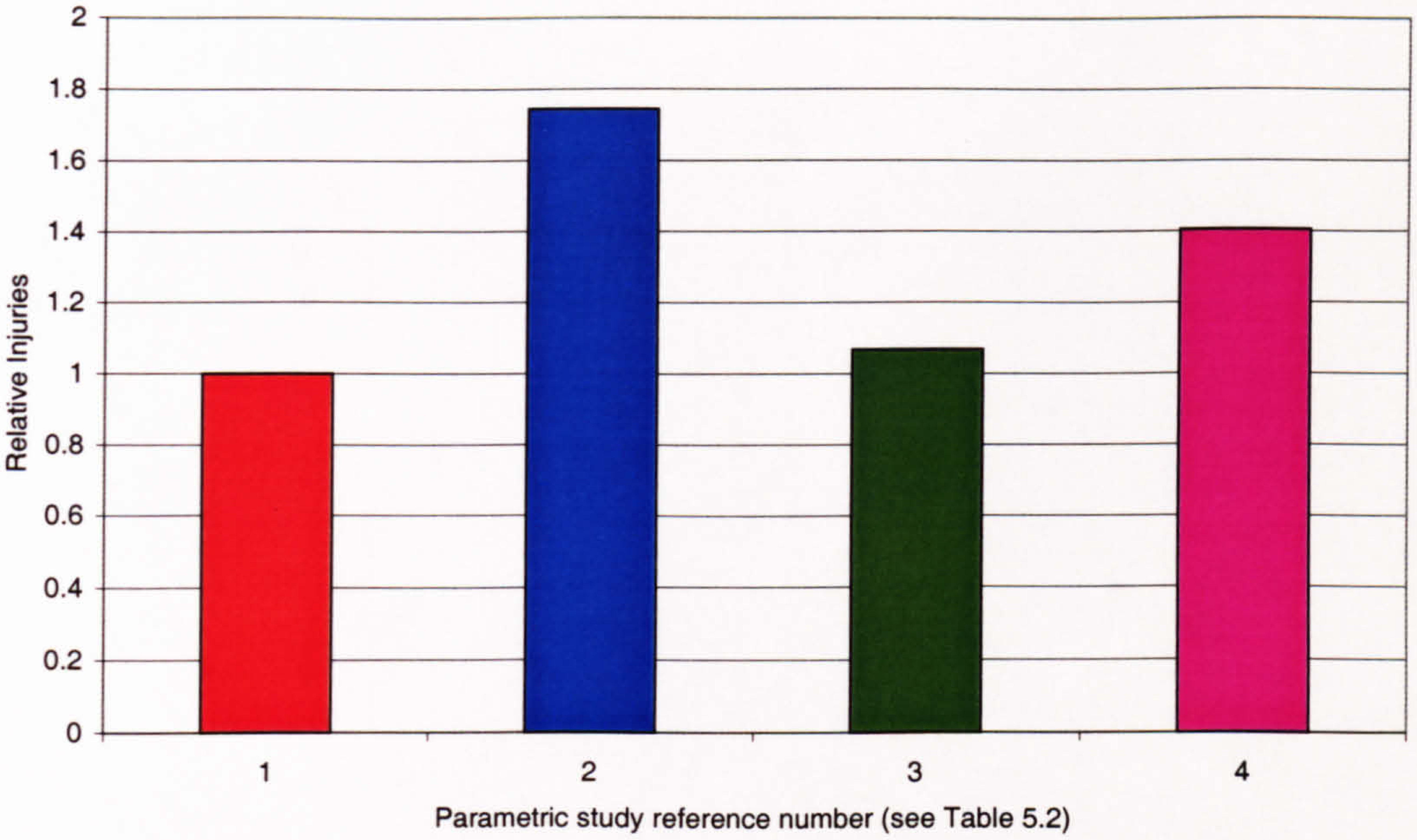


Figure D-5. Comparison of the normalised total injuries results obtained from the parametric studies for the earthquake depth

3 MAGNITUDE

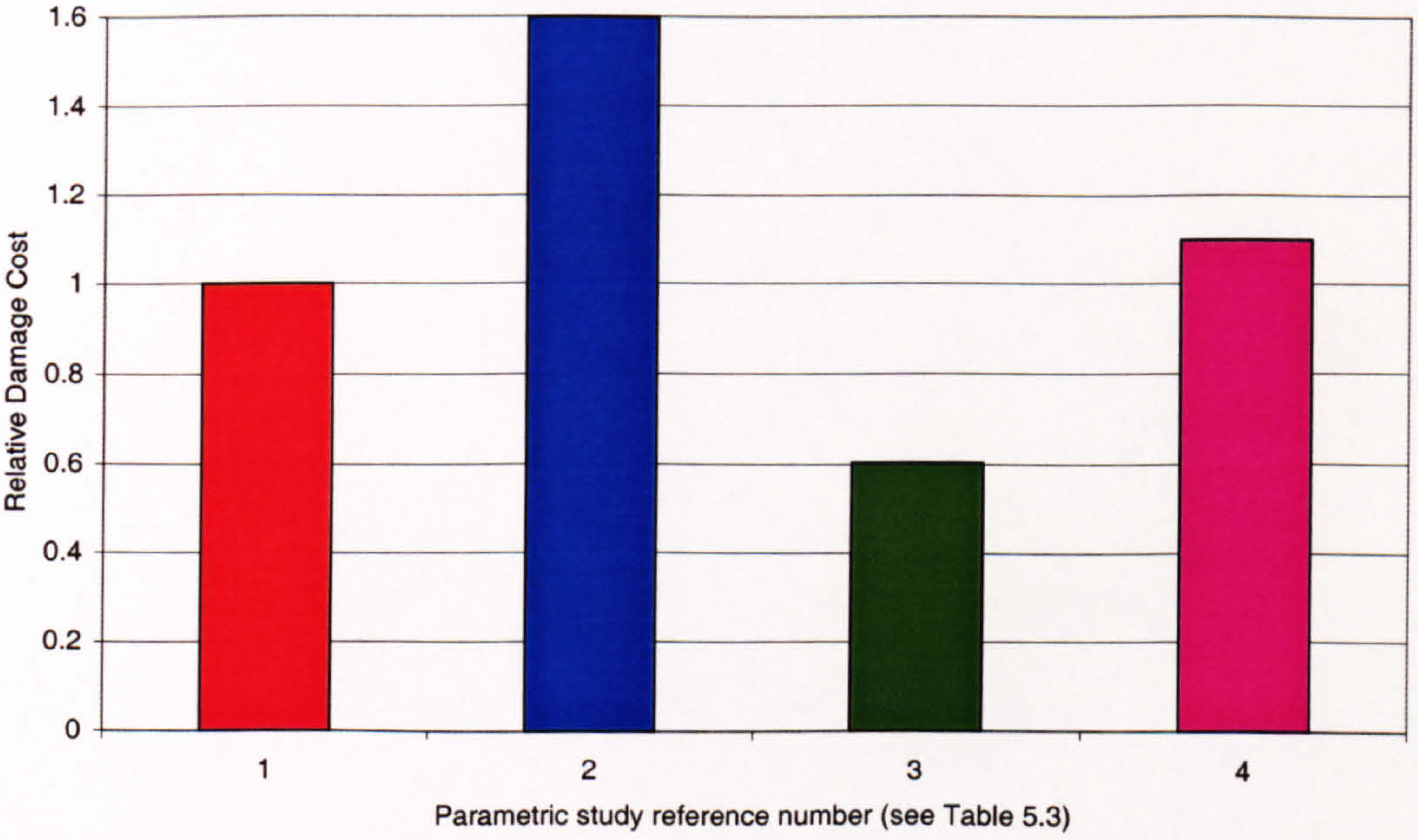


Figure D-6. Comparison of the normalised total damage costs results obtained from the parametric studies for the earthquake magnitude

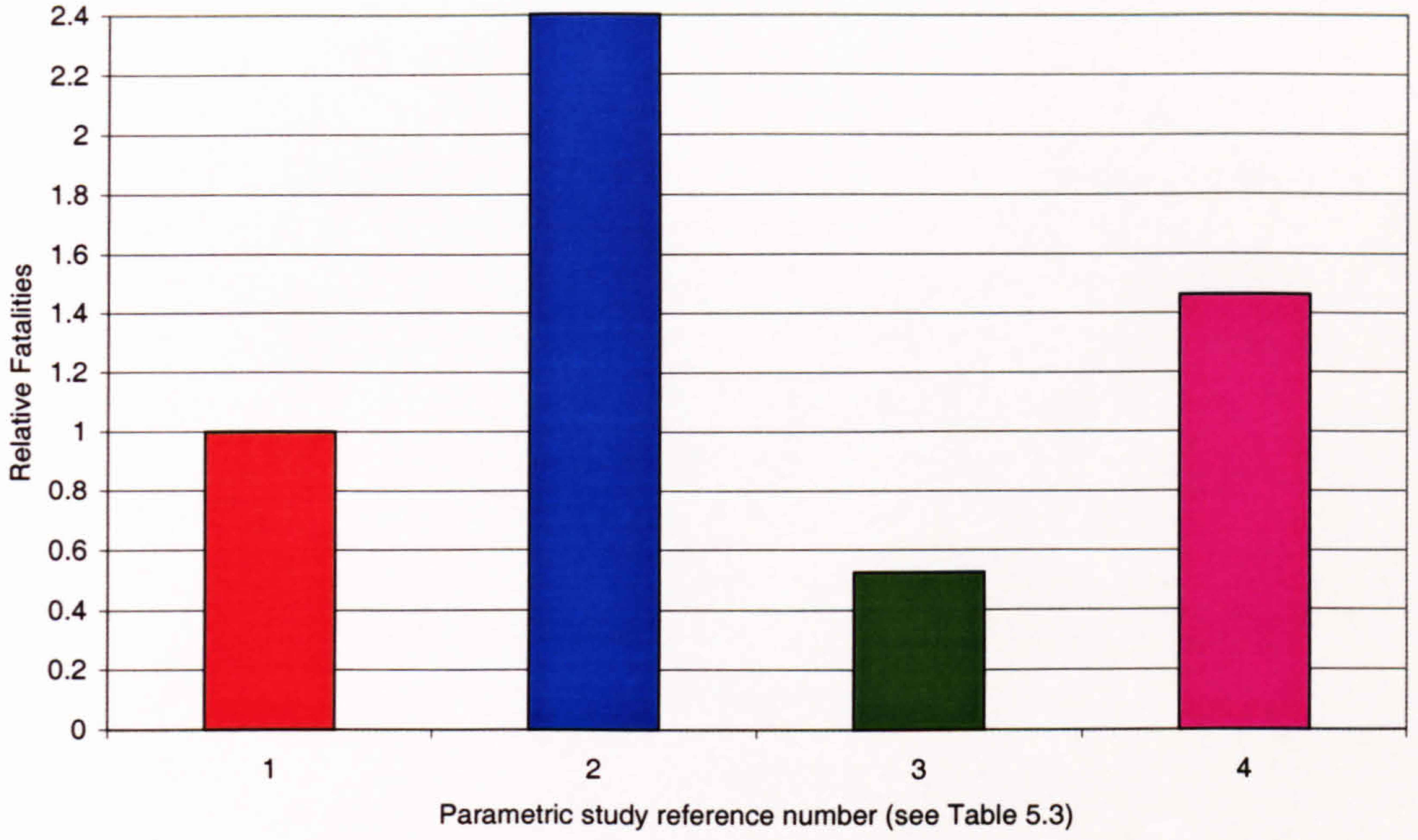


Figure D-7. Comparison of the normalised total fatalities results obtained from the parametric studies for the earthquake magnitude

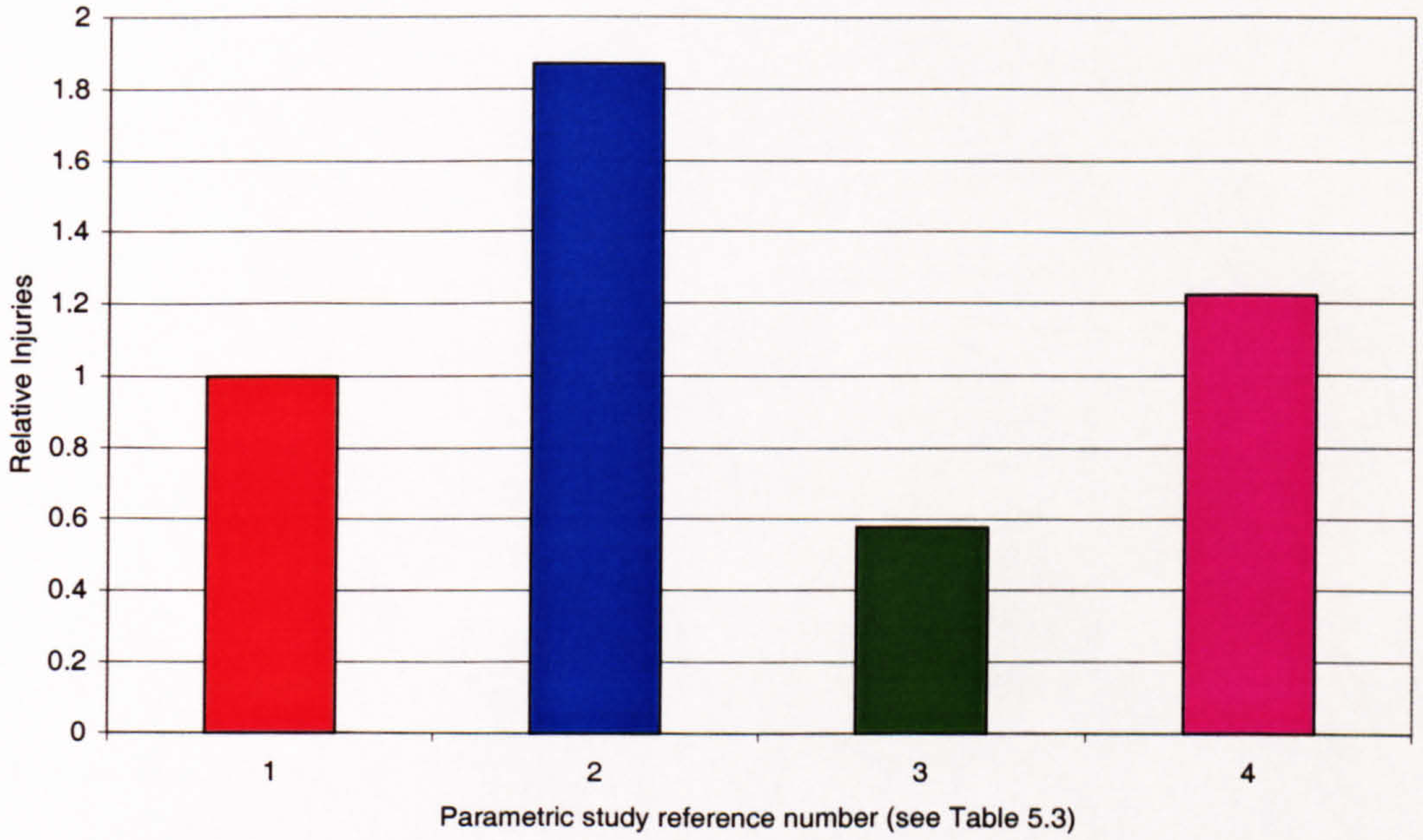


Figure D-8. Comparison of the normalised total injuries results obtained from the parametric studies for the earthquake magnitude

4 GEOLOGY

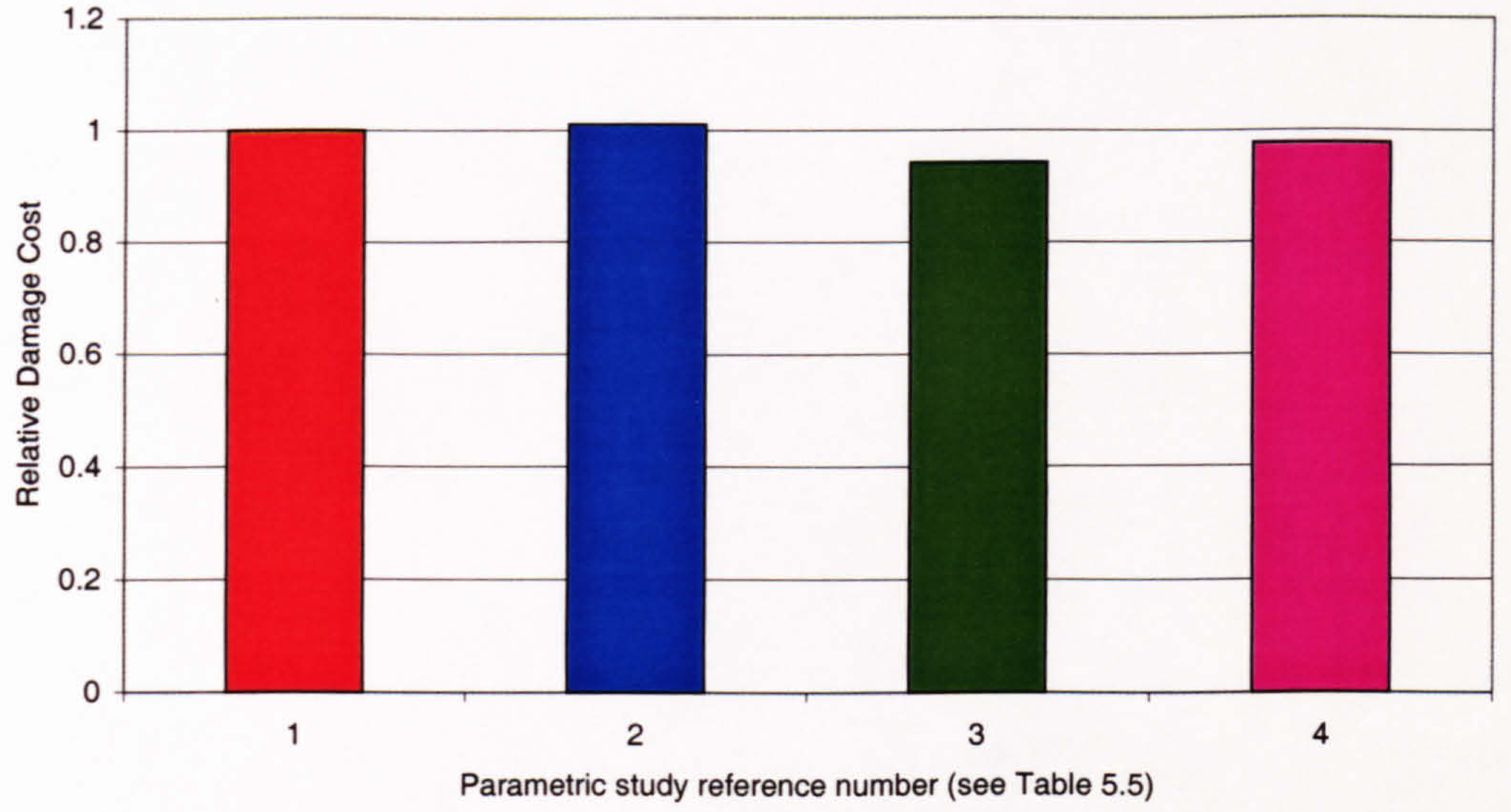


Figure D-9. Comparison of the normalised total damage costs results obtained from the parametric studies for the geology

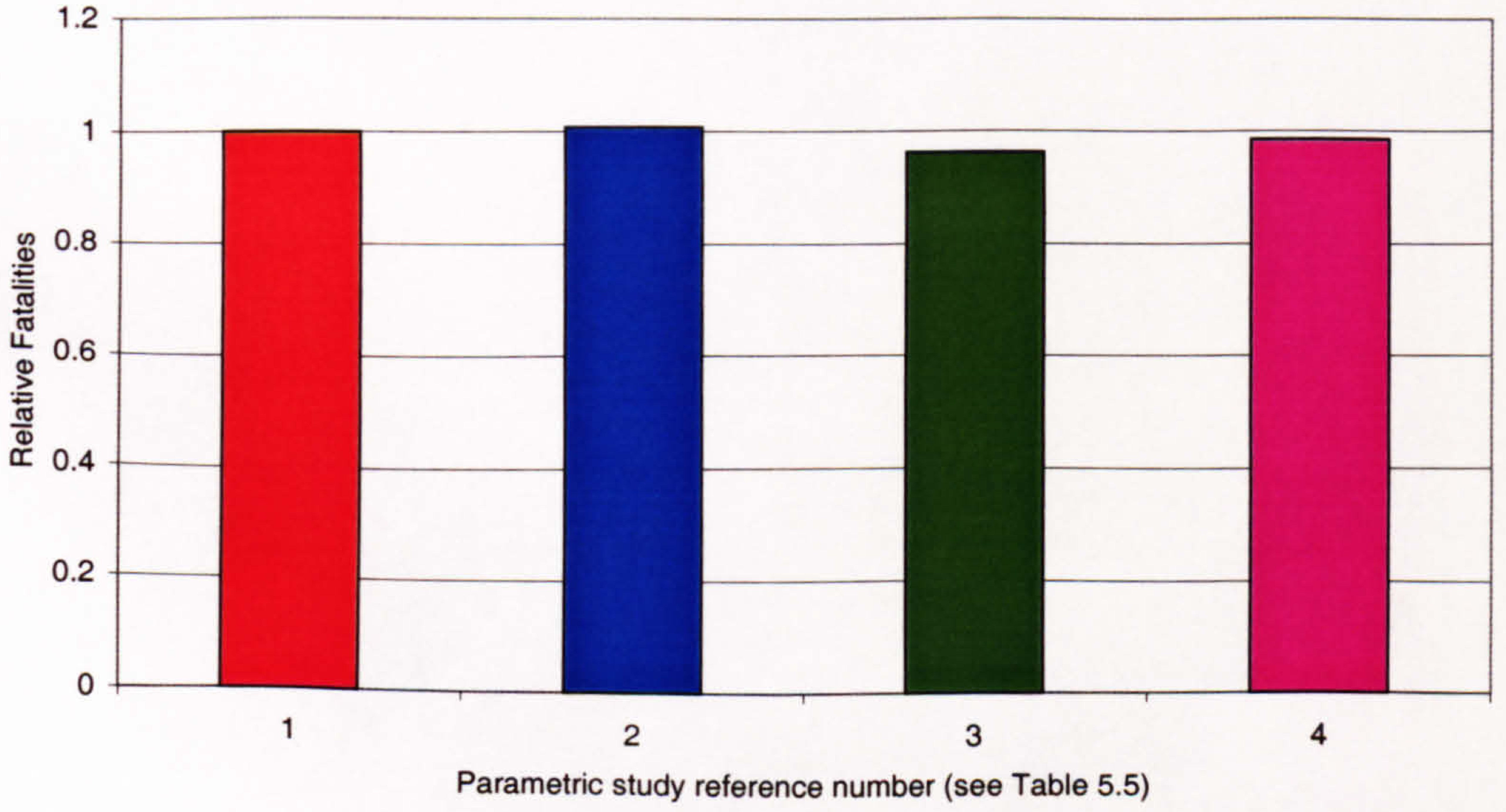


Figure D-10. Comparison of the normalised total fatalities results obtained from the parametric studies for the geology

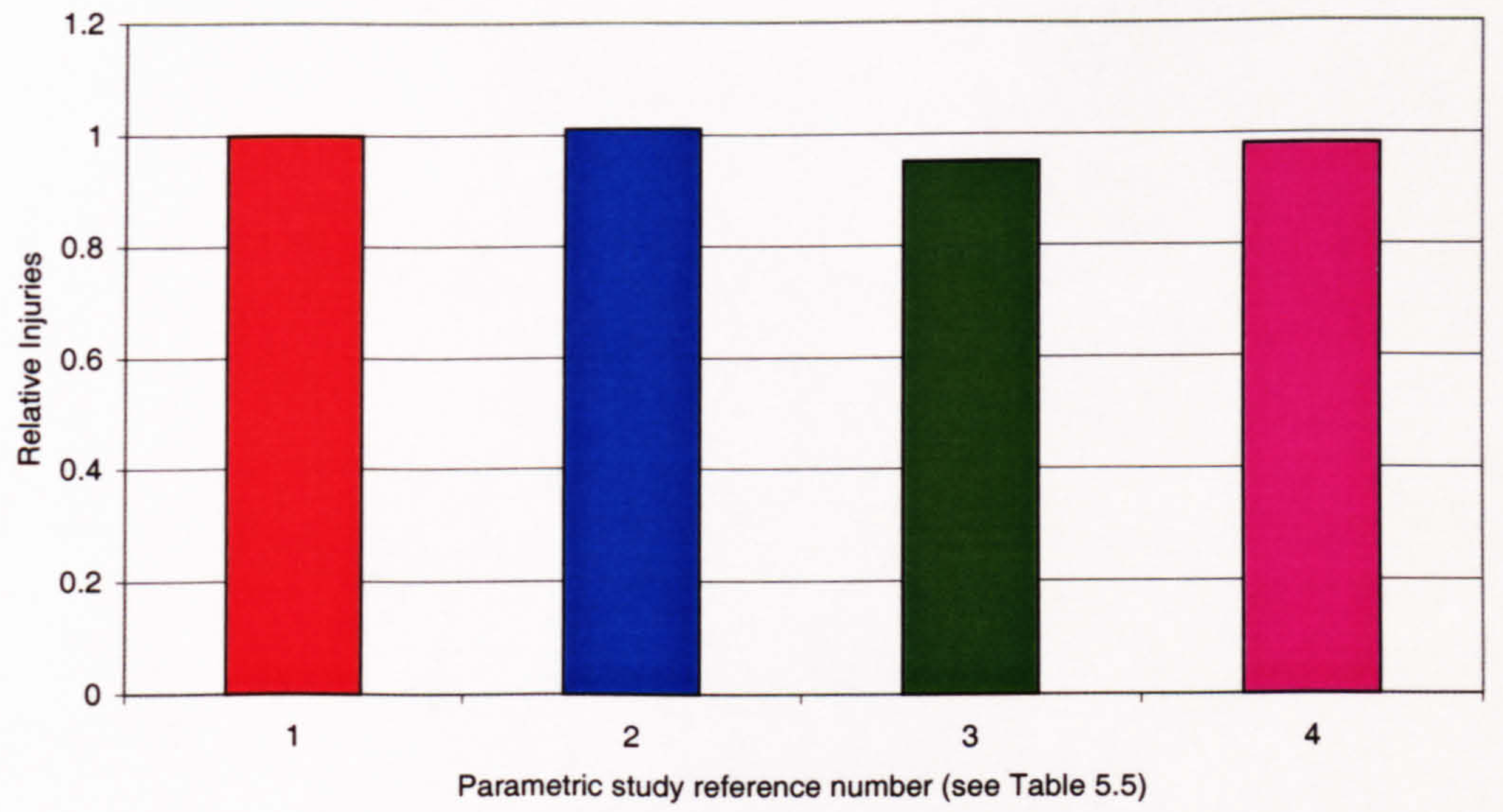


Figure D-11. Comparison of the normalised total injuries results obtained from the parametric studies for the geology

5 ATTENUATION EQUATIONS

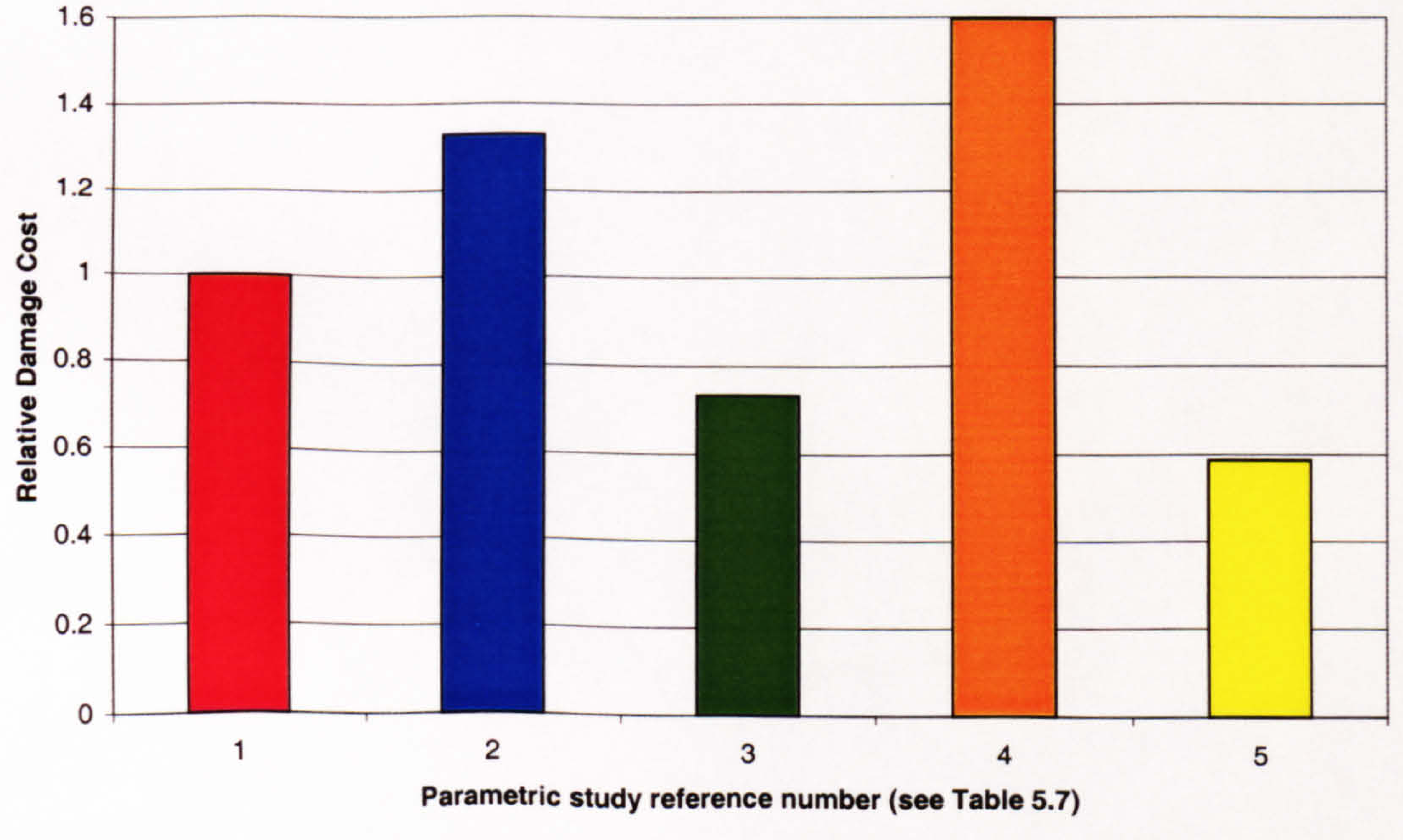


Figure D-12. Comparison of the normalised total damage costs results obtained from the parametric studies for the attenuation equations

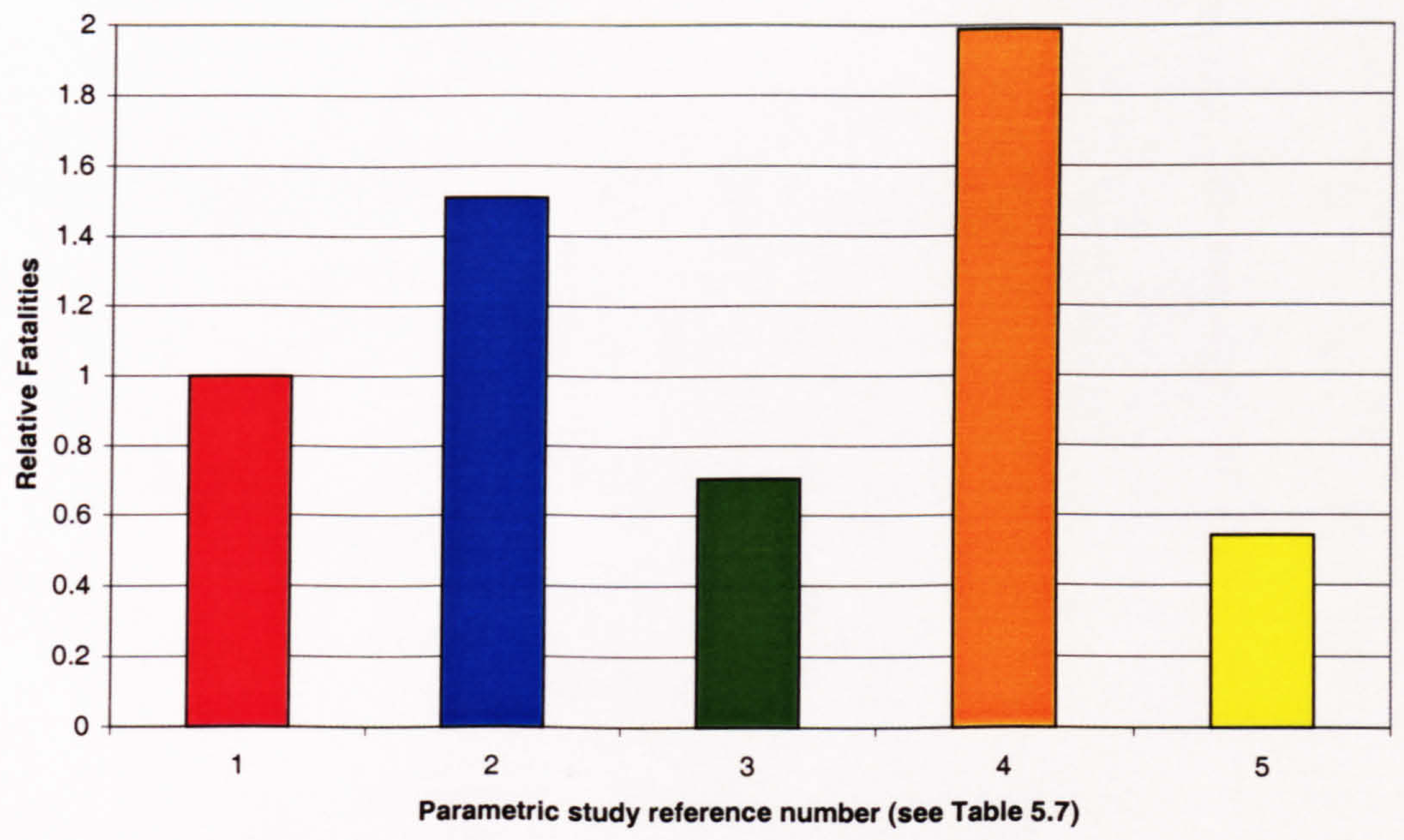


Figure D-13. Comparison of the normalised total fatalities results obtained from the parametric studies for the attenuation equations

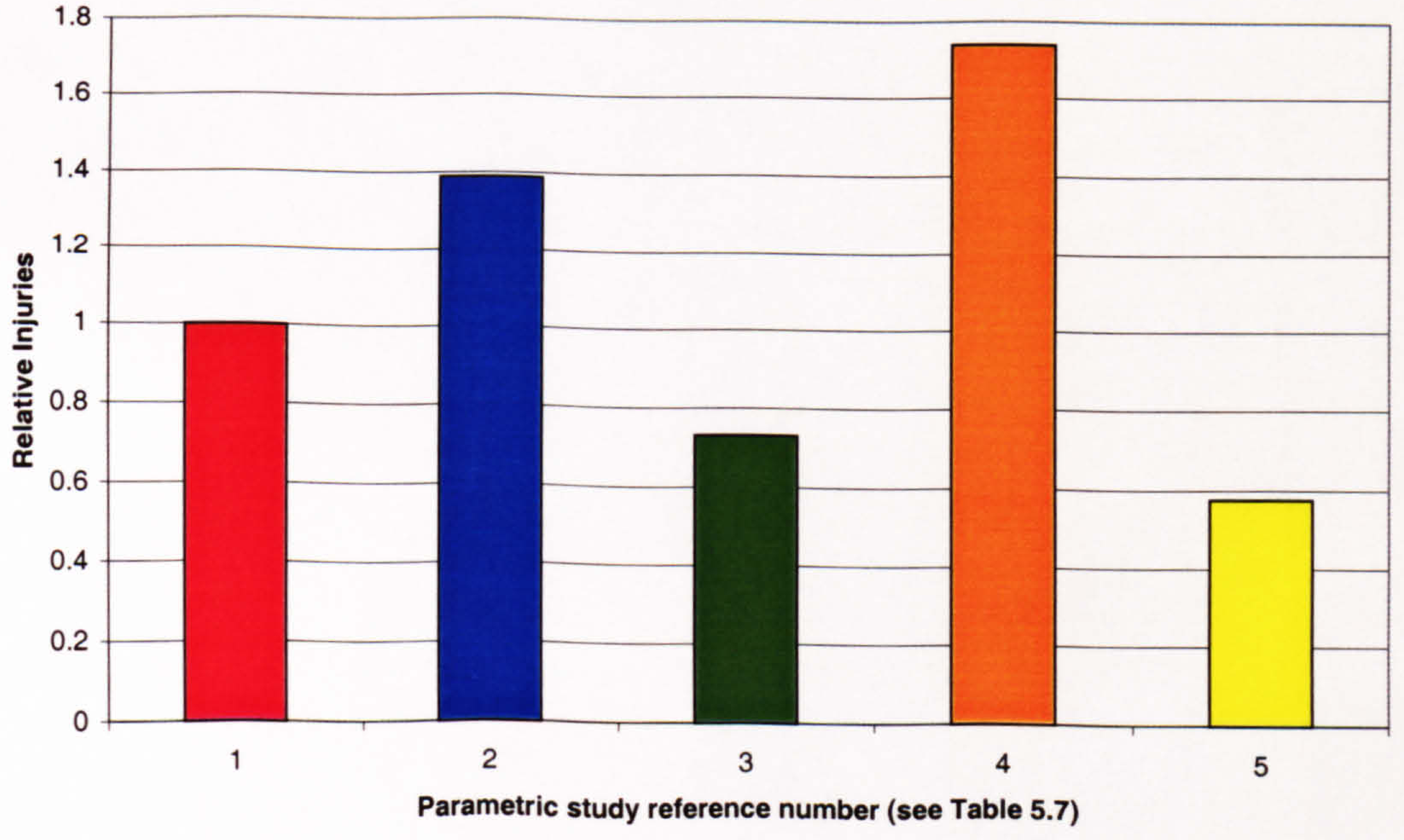


Figure D-14. Comparison of the normalised total injuries results obtained from the parametric studies for the attenuation equations

6 VULNERABILITY OF BUILDING STOCK

6.1 STUDY I

Table D-1. TABLE FOR STUDY I

		superior < 4 storeys	>4 storeys	Halls	standard substandard All
5	V	0.00	0.00	0.00	0.00
6	VI	0.00	0.00	0.01	0.06
7	VII	0.05	0.03	0.04	0.12
8	VIII	0.11	0.07	0.12	0.24
9	IX	0.25	0.16	0.30	0.48
10	X	0.40	0.29	0.60	0.80

20%		superior < 4 storeys	>4 storeys	Halls	standard substandard All
5	V	0.00	0.00	0.00	0.00
6	VI	0.00	0.00	0.01	0.08
7	VII	0.08	0.05	0.05	0.15
8	VIII	0.17	0.12	0.16	0.30
9	IX	0.38	0.27	0.40	0.60
10	X	0.60	0.49	0.80	1.00

20%		superior < 4 storeys	>4 storeys	Halls	standard substandard All
5	V	0.00	0.00	0.00	0.00
6	VI	0.00	0.00	0.01	0.05
7	VII	0.03	0.01	0.03	0.09
8	VIII	0.06	0.02	0.08	0.18
9	IX	0.13	0.05	0.20	0.36
10	X	0.20	0.09	0.40	0.60

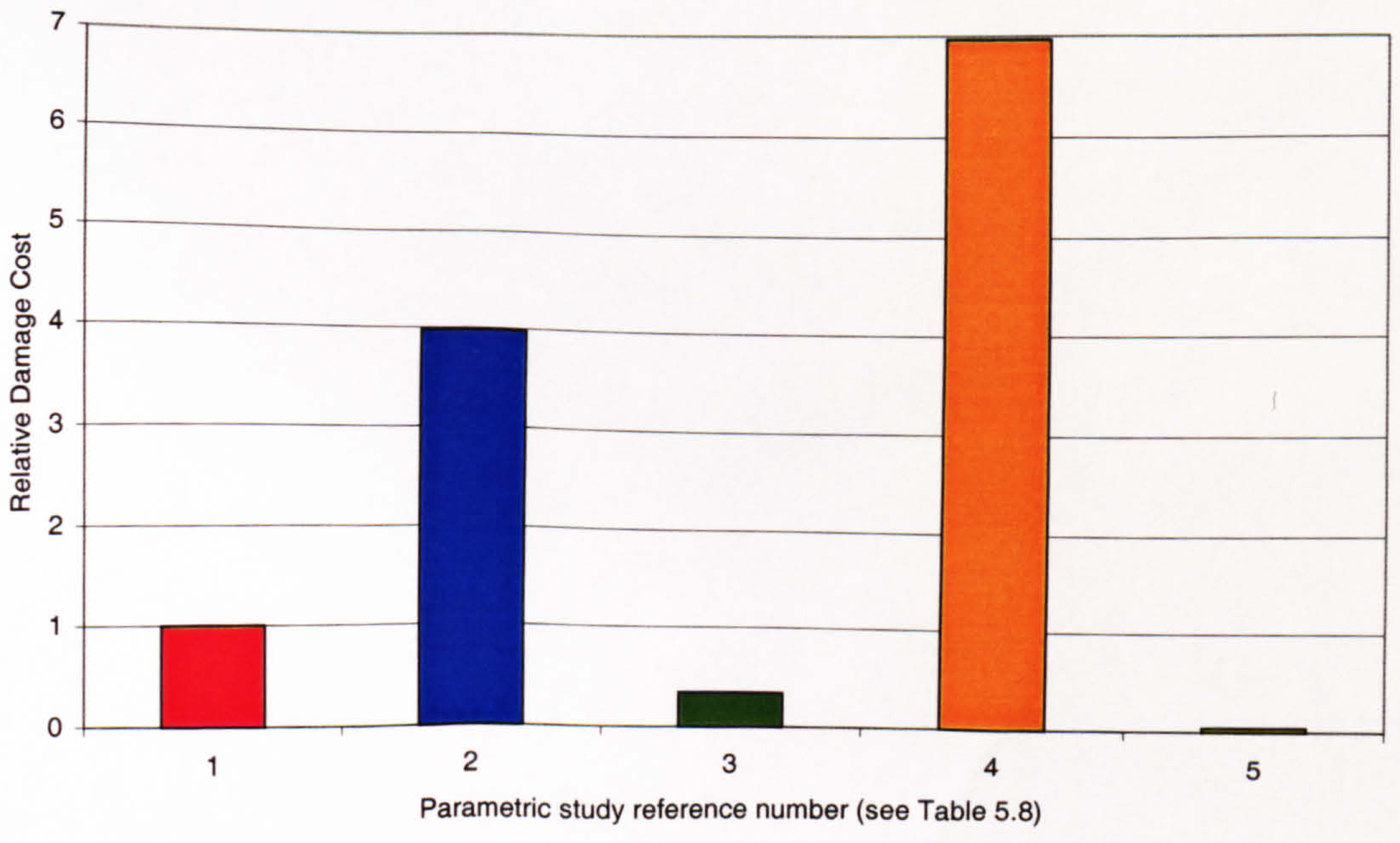


Figure D-15. Comparison of the normalised total damage costs results obtained from the parametric studies for the vulnerability (Study I)

6.2 STUDY II

Table D-2. TABLE FOR STUDY II

		superior			standard substandard
		< 4 storeys	>4 storeys	Halls	All
5	V	0.00	0.00	0.00	0.00
6	VI	0.00	0.00	0.01	0.06
7	VII	0.05	0.03	0.04	0.12
8	VIII	0.11	0.07	0.12	0.24
9	IX	0.25	0.16	0.30	0.48
10	X	0.40	0.29	0.60	0.80

0.04		superior			standard substandard
		< 4 storeys	>4 storeys	Halls	All
5	V	0.04	0.04	0.04	0.04
6	VI	0.04	0.04	0.05	0.10
7	VII	0.09	0.07	0.08	0.16
8	VIII	0.15	0.11	0.16	0.28
9	IX	0.29	0.20	0.34	0.52
10	X	0.44	0.33	0.64	0.84

0.08		superior			standard substandard
		< 4 storeys	>4 storeys	Halls	All
5	V	0.08	0.08	0.08	0.08
6	VI	0.08	0.08	0.09	0.14
7	VII	0.13	0.11	0.12	0.20
8	VIII	0.19	0.15	0.20	0.32
9	IX	0.33	0.24	0.38	0.56
10	X	0.48	0.37	0.68	0.88

minus 0.04		superior			standard substandard
		< 4 storeys	>4 storeys	Halls	All
5	V	0.00	0.00	0.00	0.00
6	VI	0.00	0.00	0.00	0.02
7	VII	0.01	0.00	0.00	0.08
8	VIII	0.07	0.03	0.08	0.20
9	IX	0.21	0.12	0.26	0.44
10	X	0.36	0.25	0.56	0.76

minus 0.08		superior			standard substandard
		< 4 storeys	>4 storeys	Halls	All
5	V	0.00	0.00	0.00	0.00
6	VI	0.00	0.00	0.00	0.00
7	VII	0.00	0.00	0.00	0.04
8	VIII	0.03	0.00	0.04	0.16
9	IX	0.17	0.08	0.22	0.40
10	X	0.32	0.21	0.52	0.72

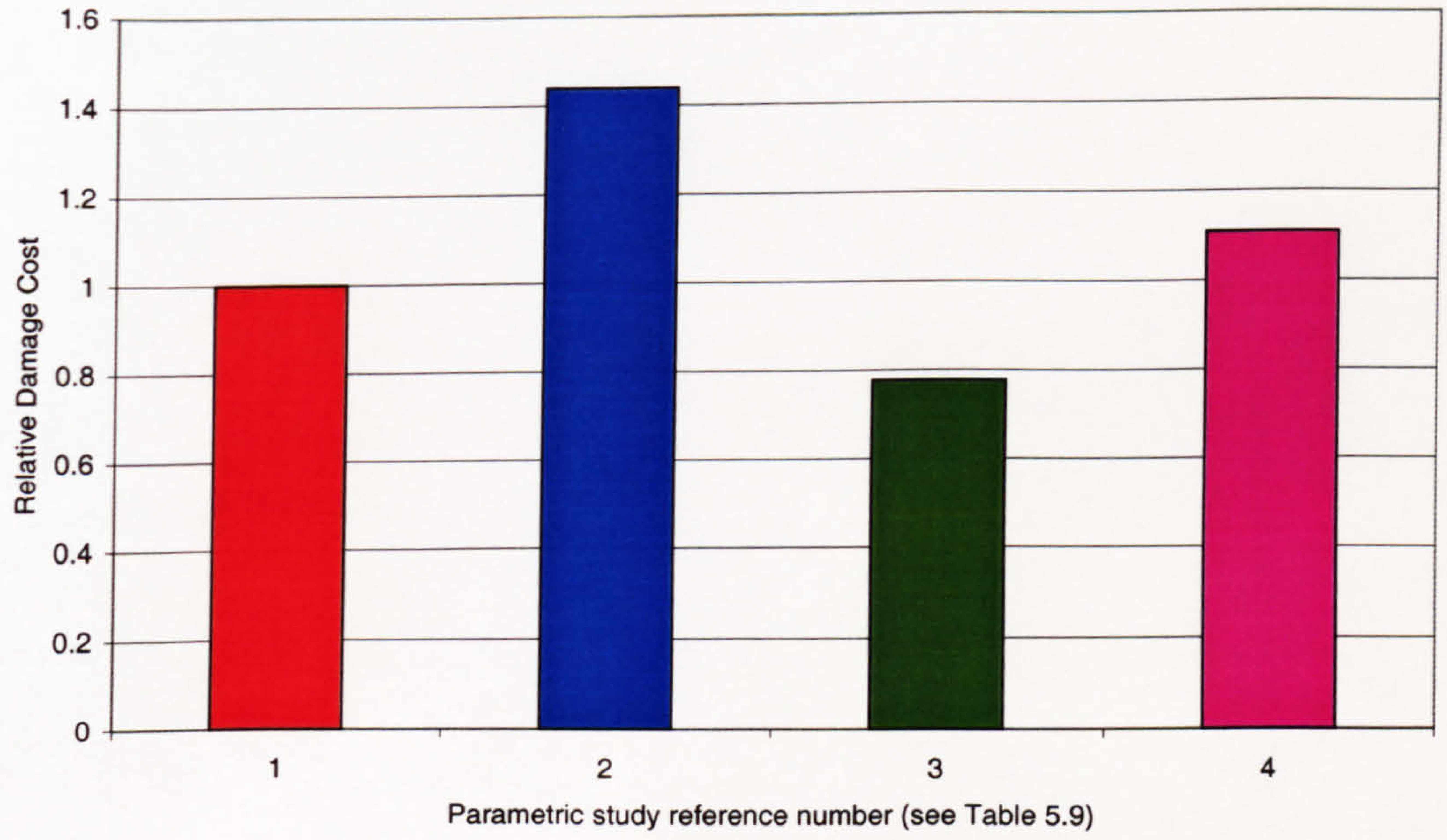


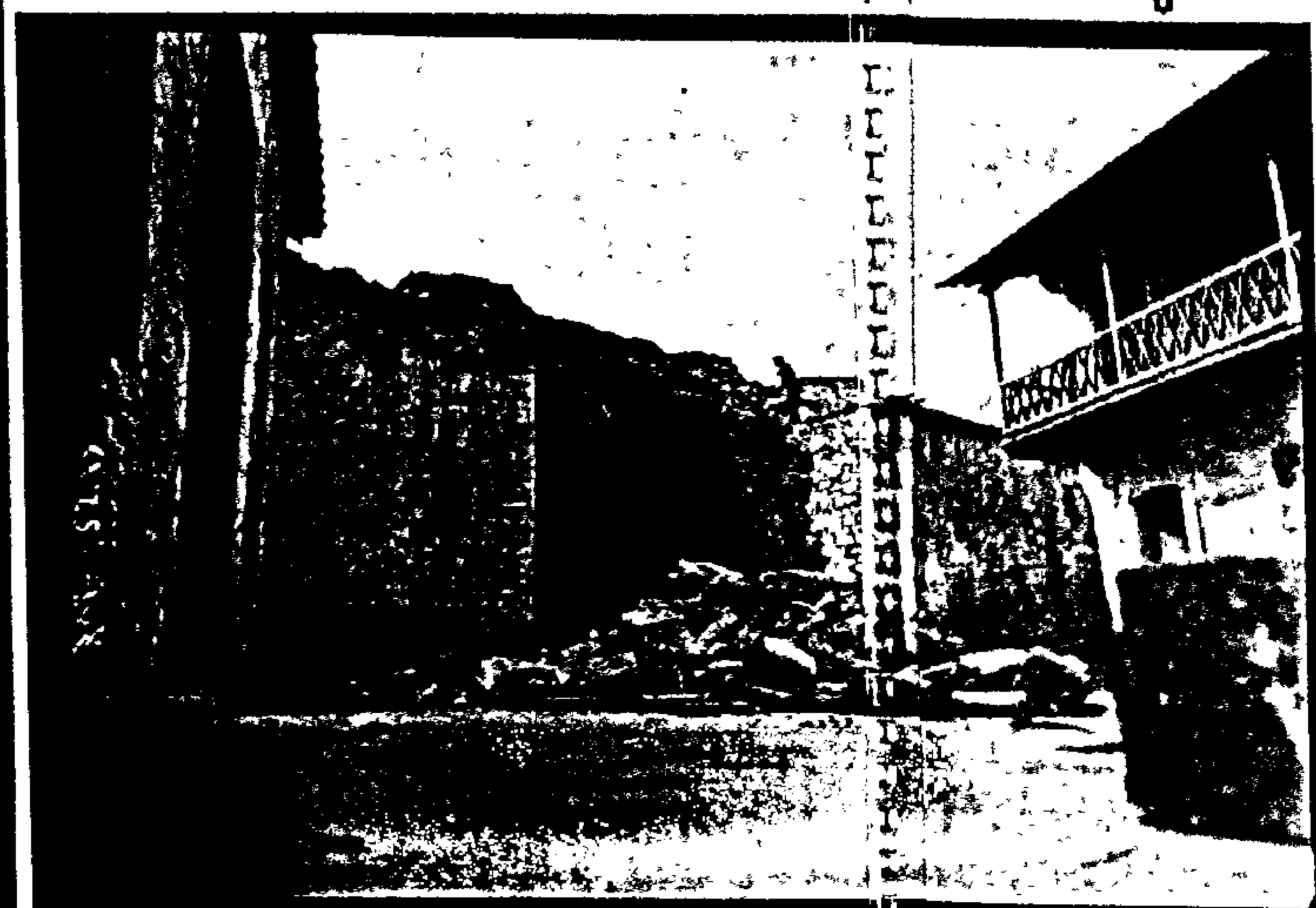
Figure D-16. Comparison of the normalised total damage costs results obtained from the parametric studies for the vulnerability (Study II)

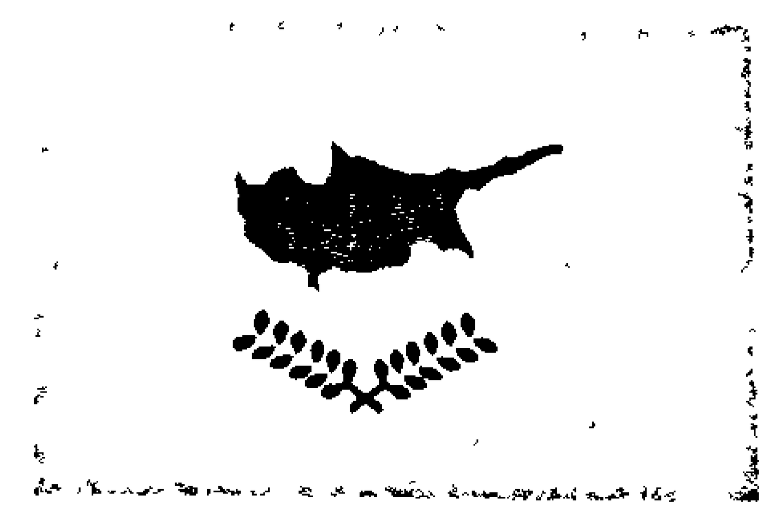
APPENDIX E

EQ-RACY Model and Input Databases

EARTHQUAKE RISK ASSESSMENT
CASE STUDY CYPRUS
EQ-RACY MODEL

PREPARED BY: S. KYTHREOTI
SUPERVISOR: DR K. PILAKOUTAS





EQ-RACY MODEL

CD-ROM

THE UNIVERSITY OF SHEFFIELD
CIVIL AND STRUCTURAL ENGINEERING DEPARTMENT