Implications of climate change for urban areas in the UK from an engineering geological perspective

ALAN FORSTER[1] MARTIN CULSHAW[2], GERRY WILDMAN[3] AND MATT HARRISON[4]

[1] British Geological Survey. (e-mail: af@bgs.ac.uk)
[2] British Geological Survey. (e-mail: mgc@bgs.ac.uk)
[3] British Geological Survey. (e-mail gwildman@bgs.ac.uk)
[4] British Geological Survey. (e-mail: mharr@bgs.ac.uk)

Abstract: Climate change is not a new phenomenon in the geological record, or even in the historical record. In the northern hemisphere geological deposits indicate that a wide range of climatic conditions have prevailed during the Quaternary ranging from Ice Ages to interglacials. Even the period since the end of the last Ice Age has shown significant variations in climatic conditions. Thus whatever the cause of climate change the consequences of changes in climate need to be considered. Cities are not self-contained entities but rely on extensive networks that supply power and resources and remove waste; both the hard engineered structures that form the cities and the infrastructure on which they are dependent can be affected by changes in climate.

In the absence of adequate records of past problems and their climatic setting the likely impacts of geohazards on the viability of a city lifestyle are best considered in the light of our understanding of the causative factors of geohazards, including climatic factors. Where possible these relationships may be tested against previous climates. This paper describes briefly the hazards that have a potential to impact on sustainable city life, how they may be influenced by climate change and how national geohazard assessments based on causal factors can be used to indicate where such impact may be significant. Recent examples are given that may be indicators of the consequences of the climatic changes that are starting to become apparent.

Résumé: Le changement climatique n'est pas un nouveau phénomène comme le démontrent les documents géologiques et les documents historiques. Dans l'hémisphère Nord, les dépôts géologiques témoignent d'une vaste gamme de conditions climatiques au cours du quaternaire, et ce, des âges glaciaires aux périodes interglaciaires. Même la période qui s'est écoulée depuis la fin du dernier âge glaciaire a contenu d'importantes variations en termes de conditions climatiques. Ainsi, quelle qu'en soit la cause, il est impératif de considérer les conséquences des changements climatiques. Loin d'être des entités autonomes, les villes s'appuient sur de vastes réseaux non seulement pour la fourniture de leur énergie et de leurs ressources mais aussi pour l'élimination des déchets ; les ouvrages de génie civil qui forment les villes et les infrastructures dont elles dépendent peuvent tous deux être affectés par les changements climatiques.

En l'absence de documentation adéquate sur les problèmes passés et leur contexte climatique, il est préférable de considérer les éventuels effets que les risques géologiques peuvent avoir sur la viabilité d'un style de vie urbain du point de vue de notre entendement des facteurs causaux des risques géologiques, y compris les facteurs climatiques. Dans la mesure du possible, ces relations peuvent être testées par rapport à des climats précédents. Cet article décrit brièvement les risques ayant un impact potentiel sur la vie urbaine durable, la façon dont ils peuvent être influencés par le changement climatique et la façon dont les évaluations nationales des risques géologiques basées sur des facteurs causaux peuvent être utilisées pour indiquer où un tel impact peut être significatif. De récents exemples sont donnés, exemples pouvant être des indicateurs des conséquences des changements climatiques qui commencent à devenir évidents.

Keywords: Climate change, geological hazards, geology of cities, urban geoscience, landslides, subsidence.

INTRODUCTION

The geological record of the Quaternary Period shows major changes of climate in the UK (United Kingdom) as it experienced a series of glacial events. Most of the evidence of early conditions has been destroyed by subsequent glaciations and the record is fragmentary but the record since the last glacial event is more complete and gives an indication of the range of climatic conditions that might be expected in the future under natural conditions. However, it is now widely accepted that the natural variation in climate is being overlaid by the consequences of human activities that have altered the composition of the atmosphere mainly with respect to increasing levels of carbon dioxide.

The scientific recording of climate is a relatively recent activity and for information on climatic conditions before about the seventeenth century observations of notable climatic events such as floods and tempest must be augmented by the interpretation of other historic records, such as changes in agriculture, to indicate past climates. Within the record of past climates it is possible to seek correlations with geohazard events that will give an insight into their consequences in the future. Where it is impossible to find a correlation between climate and geohazard events, it is still possible to estimate future activity from the application of our knowledge of the geohazard causative factors to the predicted climatic conditions.

CLIMATE IN THE FUTURE

The prediction of the climate that might be expected in the next 100 years would be a major task even without the influence of human activities. If these activities are taken into account it becomes even more difficult because of the uncertainty associated with trying to predict how the carbon dioxide content of the atmosphere will change over that period. Factors such as the rate of change of industrialisation throughout the world, the development of new technologies and the effect of an increasing acknowledgement that the production of carbon dioxide should be reduced, or even reversed, must be included in the modelling process. Thus, there cannot be a single model but a series of representative models that are appropriate to a series of possible conditions within the most likely spectrum of atmospheric compositions.

The United Kingdom Climate Impacts Programme (UKCIP) has developed climate predictions for the UK for three time periods in the future - the 2020s, 2050s and the 2080s - and for each period there is a prediction for each of four levels of increase in atmospheric carbon dioxide consequent on anthropogenic emissions being low, low-medium, medium-high and high (Hulme et al. 2002). Thus, there is a matrix of twelve different climatic conditions depending on how atmospheric composition changes and how far we look into the future. However, there is a common trend with all the predictions and the differences between them are mainly the degree of change and the rapidity with which it may happen. The most likely climate change scenario for the immediate future is of higher average annual temperatures with greater warming in the south east than the north west and summer and autumn warming to a greater extent than winter and spring. Although total rainfall may decrease slightly the winters may become wetter and the summers dryer. Extreme weather such as very hot summers and very wet winters are likely to become more frequent together with an increased number of individual extreme events such as rainstorms (Hulme et al. 2002).

GEOHAZARD IMPACT ON URBAN AREAS

The impact of a geohazard on an urban area is most apparent with regard to urban structures such as houses, shops, factories, offices, roads and railways. However, the direct financial cost of the loss of such structures is compounded by the disruption to lives, production and business that is attendant on their loss. Geohazard events outside of the urban areas also may affect them indirectly by damaging the infrastructure between them and impairing not only the passage of people and goods between towns and cities but also the services such as electricity, water, gas and waste disposal that are the support system upon which a modern city is dependent. The immediate cost of repairs to infrastructure will be borne by the companies or the government departments that operate them but this will be passed on to the users who will be mainly the inhabitants of the urban areas.

Geohazards that have affected the UK in the past include earthquakes, tsunami waves, landslides, shrinkable clay, dissolution, natural gases, collapsible deposits, compressible deposits and flooding. However, the impact of earthquakes in the UK is very slight and tsunamis are extremely rare.

Earthquakes

Minor earthquakes occur in the UK on a regular basis (Musson 2002) but the largest recorded so far was the magnitude 6.1 Dogger Bank earthquake of 1931 (Musson 1994). Although it caused considerable alarm there was little damage done. The Colchester earthquake of magnitude 4.6 in 1884 caused significant damage, including one fatality (Weston 2004). However, it is a reasonable assumption that climate is not a significant controlling factor in causing earthquakes in the UK and that damage due to minor earthquakes is likely to remain at a low level.

Tsunami waves

The Great Lisbon earthquake of 1755 caused a tsunami that resulted in a run up of 2 to 3 m on the southwest coasts of England and Ireland (Long et al. 1989). On the east coast of Scotland there is a widely occurring deposit of marine sand, dated at about 7000 years BP. This has been interpreted as the result of the impact of a tsunami wave caused by a sub sea landslide at Storeggar, off the Norwegian coast (Long et al. 1989).

Although the possibility of climate change affecting the incidence of earthquake generated and tsunami may be discounted it is possible that there could be an effect on submarine landslides. It may be possible that an increase in the temperature of the sea surrounding the UK may destabilize gas hydrates in the sediments on the continental slope leading to increased pore fluid pressure lowering the shear strength of sea floor deposits and causing submarine landslides that might generate tsunami impacts on the UK coasts.

Landslides

Landslides are common in the UK but only the most damaging are reported. However, the collective damage and cost to the country from landslides is significant. The destruction of the Holbeck Hall Hotel in Scarborough in 1993 resulted in an insurance claim for about £2 million and the cost of the emergency protection scheme needed to protect the slope from further landslides was around £1.5m (Byles 1994).

The stability of a slope is controlled by the balance between the force of gravity, which promotes landsliding, and the strength of the slope forming materials that resists it. Adverse changes in the factors which affect that balance, such as increasing the slope angle, weathering and rainfall are the triggering factors that initiate landslides.

The correlation between landslides and unusually wet weather is well known. A significant increase in landslide activity after the very wet autumn and winter of 2000 caused considerable damage to the road and rail network with a consequent cost due to both the damage done to infrastructure and to goods and travellers who were delayed (Forster

2000). Many of the ancient landslides in the UK occurred when climate was wetter, during the Pleistocene, and many examples are attributed to the Little Ice Age (AD1550–1850) when conditions were wetter and colder than today (Jones & Lee 1994).

However, it is not just the total amount of annual rainfall that is significant, it is also the intensity of the rainfall and its interaction with lithology that control landslide activity. In general, increases in landslide frequency in clay areas may take several years of above normal rainfall to become apparent because it takes time for pore water pressures to increase in relatively impermeable clay with a consequent decrease in shear strength. The association of periods of several years of above average rainfall preceding periods of higher than normal landslide activity was shown by Forster (1998) for the Dorset coast using records from 1856 to 1996. In areas of more permeable lithology the effect may be more rapid and landslides in relatively permeable ground such as slopes covered by non-cohesive head or sandy till may be initiated by a single storm in a wet season. The debris flows caused by the high intensity rainfall events that cut the A85 trunk road in Glen Ogle and the A9 at Dunkeld in August 2004 were typical of such activity. At that time parts of Scotland experience rainfall between 200 and 300% of the 30 year average for August. In the previous year a high rainfall event traversed the British Isles and caused extensive peat flows in the west of Ireland at Pollotomish Co. Mayo and on the Shetland Isles at Channerwick. The effect of the heavy rain was made worse by a preceding drought that had dried the top layers of the peat and opened cracks such that the peat was easily uplifted and flowed down slope when saturated by the torrential rain.

The likely net impact of climate change on the frequency of landslides on land will vary according to lithology with less activity in cohesive areas due to an overall drier climate and increased activity in non-cohesive and peat areas that respond rapidly to high rainfall events. Coastal slopes will also have the added influence of rising sea level and rougher seas that will promote erosion of both cohesive and non-cohesive lithologies with a contingent increased likelihood of coastal landslides. The direction in which a coast faces will be important since greater storminess and rougher seas will attack exposed coasts faster than sheltered ones. Even greater summer dryness may offer little respite since the formation of deep desiccation cracks near to a cliff edge may create potential failure surfaces that will promote increased soil fall and toppling failures.

Shrinkable clay

The volume of a clay soil changes as water is taken up or released by its clay minerals. The amount of change is controlled by the type and proportion of clay minerals present. On a national basis the total cost of the damage done by shrinkable clay soils is much greater than that caused by landslides. Damage is usually caused in dry years as the soil volume shrinks especially where trees remove moisture from the ground near to a building's foundation and cause clay soil to shrink to depths of several metres. In 1991, after the preceding year's drought, insurance claims for damage due to shrinkable clay soils peaked at £500 million and claims are currently estimated to be about £3-400 million per year.

The effect of shrinkable clay soils is not confined to buildings. After the drought of 2003 the councils in south-eastern England estimated the cost of repairing roads damaged by the drought to be £15 million of which Peterborough City Council, alone, faced a bill of £2.4 million for repairs (Anon. 2003).

In areas of shrinkable clay a higher frequency and severity of summer drought would cause a significant shrinkage of clay soils causing damage to older buildings whose foundations may not be designed for such stress. This may be particularly severe in the south east of the country where most shrinkable clay soils are found and summer temperatures are expected to show the greatest increase. Wetter winters would not necessarily compensate for the summer's drought if rainfall occurs in the form of intense short bursts of heavy rain, because rain would be more likely to be lost by surface runoff to land drains rather than infiltrate the ground and allow clays to rehydrate. If there were an alternation of summer drought and wet winters the damage might be worsened if the desiccation cracks formed on shrinkage become infilled with debris, since this would constrain the recovery to the original volume of the clay on taking up water in winter, thus resulting in heave or lateral pressure that could cause more damage to nearby structures.

Dissolution

The soluble rocks encountered in the UK are, in order of increasing solubility, limestone, chalk, gypsum and rock salt. In the past, rock salt extraction by solution has caused many subsidence problems, particularly in Cheshire, but it is so soluble that natural processes have removed salt from the near-surface zone and natural subsidence events are rare. Gypsum is sufficiently soluble to dissolve naturally over a time scale significant to human affairs but not so soluble that gypsum deposits have been removed entirely from the near-surface zone. Subsidence due to the dissolution of Permian gypsum deposits is well known in the Ripon area of North Yorkshire, northern England and has caused considerable damage. Based on an understanding of the distribution of geological strata, groundwater flow patterns and the dissolution process it has been possible to produce hazard maps and appropriate planning guidance to minimise its impact (Cooper & Calow 1998). Where construction is necessary in areas of known gypsum dissolution hazard, foundations can be designed to span safely the most likely dimensions of subsidence events.

Strong limestone such as the Carboniferous Limestone of northern and western England and South and North Wales dissolves slowly and is capable of sustaining large stable cavities. However, chalk is a weaker limestone that is less able to form stable cavities but is more prone to natural subsidence caused by gradual dissolution to form circular depressions known as sinkholes (Culshaw & Waltham 1987). However, in both strong and weak limestone, subsidence over natural cavities may occur if local flooding at times of intense rainfall washes loose superficial material into natural cavities creating new, or increasing the activity of existing sinkholes.

The effect of climate change on the potential for the dissolution of soluble rocks is not clear but any changes in the pattern of groundwater flow may be significant. If the net rainfall becomes greater than at present or if rainfall becomes more intense this may result in more frequent flooding of gypsum and limestone cave systems that could cause greater dissolution to take place in areas that had, in the past, remained dry. Alternatively, if the climate becomes dryer and the water table falls then new drainage pathways from the surface may open up and new sinkholes may form. Another possibility is that increased carbon dioxide in the atmosphere will result in rainfall with a higher level of dissolved carbon dioxide and greater acidity that will enable it to dissolve more carbonate rock as it passes through the ground. However, this may only be significant on a geological time scale.

Hazardous Gases

Radon, methane and carbon dioxide are naturally occurring gases that may pose serious hazards to those visiting unventilated underground spaces. Radon is a radioactive gas that may cause cancer if exposure to it is prolonged. It is produced by the decay of naturally occurring radioactive minerals that are present in small amounts in some rocks such as granite.

Methane occurs naturally and is commonly found in Carboniferous rocks such as sandstone, coal and shale where it is derived mainly from the organic content in the coal and shale but commonly accumulates in the pore spaces of the sandstone. It forms an explosive mixture with air when the proportion of methane is between 5% and 15% by volume and can be ignited by a spark or flame. This was the cause of the Abbeystead water pumping station explosion in 1984 when 16 people were killed and 36 were injured (Anon 1984).

Carbon dioxide and stythe gas (blackdamp) are naturally occurring asphyxiating gases that migrate through fissured ground that may accumulate in subsurface confined spaces and persons entering such places would suffer asphyxia and, unless removed rapidly and resuscitated, death. Carbon dioxide is heavier than air and may displace it in open excavations in still air conditions.

The effect of climate change on natural hazardous gases may not be significant unless greater extremes of weather are associated with more rapid and greater changes in atmospheric pressure that may promote the release of gases from the ground into underground spaces such as unsealed basements and tunnels as barometric pressure drops.

Collapsible deposits

Collapsible loessic deposits are uncommon in the UK and are largely restricted to the south of England. They comprise wind deposited silts with an open textured, weakly-bonded granular structure that is metastable and may collapse suddenly if a critical loading is exceeded or if it is saturated whilst under a sub-critical load. Since the south is expected to become dryer and warmer it is unlikely that collapse will become more frequent and it may decrease.

Compressible deposits

Compressible ground typically comprises saturated organic soils such as alluvial clays, laminated lacustrine deposits or peat that will compress under load as water is squeezed rapidly from the pores and interstitial spaces. A dryer climate with periods of significant drought may cause peat deposits to dry out and shrink causing damage to structures built on them. The damage to roads experienced in the eastern counties of England in 2003 may have been due, in part, to the shrinkage of peaty soils. In wetter areas the water content would probably remain the same and the potential for compression would remain unchanged.

Flooding

Increased rainfall in winter may have serious implications for flooding. Although flooding may not usually be classed as a geohazard, geology has an important influence on the severity of the hazard due to its controlling effect on infiltration into the ground, on water storage capacity in the sand and gravel deposits that are often associated with river valleys and on the rate of change in the position of the water table. Such 'groundwater' flooding is very significant in wide river valleys such as those of the Rivers Thames and Trent in England and in chalkland areas of southern England where intermittent springs are common. Rainfall-induced landslides, as noted above, may also affect the impact of local flood events. Geological information can also help in planning for flood avoidance because an understanding of past flooding levels as revealed by their alluvial deposits can assist in predicting future maximum flooding levels.

An example of the influence of landsliding on the damage caused by flooding during high intensity rainfall events was that at Lynmouth, in Devon, south west England, on the 16 August 1952. The damage was, at least in part, accentuated by shallow debris flows in superficial material on the steep valley sides of the streams draining off Exmoor (Gifford 1953, Kidson 1953, Green 1955). These failures formed minor dams that impounded the waters in the heavily swollen streams. When they failed in rapid succession, a large pulse of water charged with rocks and soil flowed downstream, increasing the density of the floodwater and its ability to cause damage. Nearby, exactly 31 years later on the 16 August 2004, another rainstorm caused severe flooding in the village of Boscastle which lies in a similar topographical setting but, in this case, the area the valley slopes were not covered with superficial material and few landslides occurred that could form landslide dams or add material to the flow to make the flood waters more damaging.

PREDICTING THE CONSEQUENCES OF CLIMATE CHANGE

There are two ways in which hazards can be predicted - probabilistically and deterministically. The probabilistic method seeks to predict future occurrence on the basis of the record of past events. It assumes that the conditions that caused an event have remained constant and that the potential for that event to reoccur also remains constant. This method has significant limitations when dealing with the prediction of geohazards. Firstly, climatic conditions have not remained constant in the past and the conditions in the future are far from certain. Secondly, the method requires a large and complete record of past events that may be analysed statistically to give a probabilistic prediction of the pattern of events in the future. Lastly, for some events such as landslides, the event itself alters the conditions rendering a repetition of the event impossible; once a landslide mass has failed and moved down a slope it cannot repeat the same movement again. Thus the probabilistic method is severely limited in the prediction of many geohazards.

The deterministic method is based on the combination of the factors that cause the hazard and is independent of past history although the record of past events may be a useful, though imperfect, guide to the validity of the prediction. The more causal factors that can be identified, captured and combined, the more accurate will be the prediction.

The British Geological Survey has completed national hazard assessments at 1:50 000 scale for the geohazards landslide, shrinkable clays, compressible soils, collapsible soils, soluble rocks and running sands (Anon. 2004) based primarily on the national digital geological map (Harrison and Forster 2003). For each hazard appropriate factors were combined to give a rating on a five-point scale of the potential for a hazard to become active. Thus, for landsliding, slope angle, lithology and implied geotechnical behaviour are combined to give an indication of how close the ground is to failure if one factor were to increase in severity or another to be added.

The enhancement of the accuracy of the national assessments by the addition of other locally available datasets, such as spring lines or weathering grade, for areas in Wellington in Somerset (Gibson et al. 2004), Builth Wells (Forster and Wildman 2005) and London (Forster et al. 2003) has demonstrated the flexibility of the deterministic approach. Thus, a causal factor weighting for climate may similarly be added once the effect of the appropriate climatic scenario on each geohazard has been determined. If this is done on the basis of future climates then it will allow appropriate measures to be taken to mitigate the expected consequence. This may include measures such as changes to building regulations requiring deeper foundations in areas of shrinkable clay that will become more prone to droughts or changes to planning regulations to avoid areas that will become prone to flash flooding and debris flows.

CONCLUSIONS

It is likely that the most important consequences of climate change for geohazards in the UK will be more widespread and more rapid coastal erosion, more subsidence, more floods and more landslides but not necessarily spread uniformly across the country.

Since it is unlikely that the climate could be maintained at an optimum state that would minimize the incidence of geohazards, assuming such an optimum state could be agreed internationally, the best response will remain the same as at present: a detailed understanding of the processes that cause geohazards will enable the areas prone to them to be predicted using a deterministic methodology that can incorporate an input from the appropriate climatic scenario as a causal factor. Care will be needed in using probabilistic methods that assume 'steady state' in a situation in which one of the major causal factors (climate) is changing rapidly.

To improve our understanding of geohazard processes, and hence reduce the risk, it is necessary to sustain activity to gather new information about the factors that cause geohazards, to build national and international databases containing this information and to develop better 3D spatial models of the ground affected.

Having identified hazardous areas, their impact may be eliminated or mitigated by avoidance or engineered structural design, controlled through the planning process.

The UK has always been affected by both geohazards and a changing climate and whatever climate change occurs in the future the same geohazards will be present to a greater or lesser degree. It is important that the drivers of climatic change and the causative factors that control geohazards continue to be studied because such knowledge will enable us to better predict how geohazards are likely to be affected and improve the measures needed to control and mitigate the effects.

Acknowledgements: This paper is published with the permission of the Executive Director of the British Geological Survey (NERC).

REFERENCES

ANON. 1984. The Abbeystead explosion: a report of the investigation by the Health and Safety Executive into the explosion on 23rd May 1984 at the valve house of the Lune/Wyre Water Transfer Scheme at Abbeystead. ISBN: 0118837958.

ANON. 2003. Drought damaged roads will close without emergency cash. *New Civil Engineer*, 13 November. EMAP Publishing.

ANON. 2004. Britain beneath our feet - an atlas of digital information on Britain's land quality, underground hazards, resources and geology. (Ed. I. Jackson). British Geological Survey Occasional Publication No. 4. Keyworth, Nottingham.114p. http://www.bgs.ac.uk/britainbeneath/hazards_introduction.html

BYLES, R. 1994. Scarborough Rock. New Civil Engineer, 3 February. 18-20.

COOPER, A.H. & CALOW, R.C. 1998. Avoiding gypsum geohazards: guidance for planning and construction. British Geological Survey Technical Report WC/98/5.

CULSHAW, M.G. & WALTHAM, A.C. 1987. Natural and artificial cavities as ground engineering hazards. *Quarterly Journal of Engineering Geology*, **20**, 139-150.

FORSTER, A. 1998. The Engineering Geology of the Sidmouth District, 1:50 000 Geological Sheet 326/340. British Geological Survey Technical Report WN/98/1.

FORSTER, A. 2000. Deluges of grandeur. *Ground Engineering*, December, p8.

FORSTER, A. & WILDMAN, G. 2005. Geology of England and Wales sheet 196 Builth Wells, Scale 1:50 000. Map 5: Landslide Susceptibility. British Geological Survey, Keyworth, Nottingham

FORSTER, A, WILDMAN, G. & POULTON, C. 2003. Landslide potential modelling of North London. British Geological Survey Internal Report IR/03/122R.

GIBSON, A, FREEBOROUGH K.A., HALL, M., POULTON, C., WILDMAN, G. & FORSTER, A. 2004. Landslides and mass movement processes and their distribution in the Wellington District (Sheet 311). British Geological Survey Internal Report, IR/04/145.

GIFFORD, J. 1953. Landslides on Exmoor caused by the flood of 15th August 1952. *Geography*, **38**, 9-17

GREEN, G.W. 1955. North Exmoor floods, August 1952. Bulletin of the Geological Survey of Great Britain, No **7**, 68-84.

HARRISON, M. & FORSTER, A. 2003. The application of GIS modelling to the assessment of geohazard potential at a national scale. Proceedings of the Annual Conference of the International Association for Mathematical Geology. Sept 7-13 Portsmouth.

HULME, M., JENKINS, G.J., LU, X., TURNPENNY, J.R., MITCHELL, T.D., JONES, R.G., LOWE, J., MURPHY, J.M., HASSELL, D., BOORMAN, P., MCDONALD, R. & HILL, S. 2002. Climate change scenarios for the United Kingdom: The UKCIP02 Scientific Report, Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich, UK.

JONES, D.K.C. & LEE, E.M. 1994. Landsliding in Great Britain. Report for the Department of the Environment, Her Majesty's Stationery Office, London

KIDSON, C. 1953. The Exmoor storm and the Lynmouth floods. *Geography*, **38**, 1-9

LONG, D., DAWSON, A.G. & SMITH, D.E. 1989. Tsunami risk in northwestern Europe: a Holocene example. Terra Nova, 1, 532-537.

MUSSON, R.M.W. 1994. "A Catalogue of British Earthquakes", British Geological Survey Technical Report No WL/94/04.

MUSSON, R.M.W. 2002. Seismicity and earthquake hazard in the UK. British Geological Survey web site http://www.earthquakes.bgs.ac.uk/

WESTON, A-J. 2004. Earthquake impact scenarios: a GIS-based case study for Colchester, UK. Unpublished PhD thesis, University of East Anglia.