# Climate change impact forecasting for slopes (CLIFFS) in the built environment

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**Abstract:** Topography, geology, climatic conditions and human modification result in slope processes having an important impact on the built environment and infrastructure in the UK. Many tens of thousands of people live with continuing slope instability or the threat of instability of actively eroding coastlines and unstable inland slopes. Thousands of kilometres of transport links and utilities are located in areas susceptible to slopes failure.

At present, planning and design involving assessments of slope stability often take place based on relatively static information (represented by maps, soil parameters, hydrological models, etc.). However, changes in dominant input parameters (such as precipitation and temperature) are now clearly occurring at a rate that demands a fundamental review of our perceived steady state approach. It is questionable whether steady state information is relevant at best, or misleading at worst. A range of forecast scenarios of slope instability and distribution are needed, with each scenario being associated with a certain level of confidence and a measure of severity of impact on the built environment.

Although detailed processes or individual site conditions are being addressed, general process-response issues are still not well understood or researched - a problem exacerbated by poor communication in this multi-disciplinary field. A UK EPSRC-funded network aims to address this by bringing together academics, research and development agencies, stakeholders, consultants and climate specialists to synthesise knowledge in the broad field of Climate Change Impact Forecasting For Slopes (CLIFFS network). The potential usefulness of this network will be highlighted in this paper through discussions of slope instability impacts on the built environment, a summary of climate change scenarios and an analysis of the challenges facing those involved in planning, designing and monitoring slopes, including issues of communicating risk and uncertainty of forecasts of slope instability.

**Résumé:** La topographie, la géologie, les conditions climatiques et la modification humaine ont comme conséquence des processus de pente ayant un impact important sur l'environnement établi et l'infrastructure au R-U. Beaucoup de dizaines de milliers de personnes vivent avec l'instabilité de pente ou la menace de l'instabilité des littoraux activement d'érosion et des pentes intérieures instables. Des milliers de kilomètres de liens et d'utilités de transport sont placé dans les secteurs susceptibles de l'échec de pentes.

Actuellement, la planification et la conception impliquant des évaluations de stabilité de pente a lieu souvent basé sur l'information relativement statique (représentée par des cartes, des paramètres de sol, des modèles hydrologiques, etc.). Cependant, les changements des paramètres dominants d'entrée (tels que la précipitation et la température) se produisent maintenant clairement à un taux qui exige un examen fondamental de notre approche perçue d'état d'équilibre. Il est incertain si l'information d'état d'équilibre soit appropriée au mieux ou trompant à plus mauvais. Une gamme des scénarios prévus de l'instabilité de pente et la distribution sont nécessaires, avec chaque scénario étant associé à un certain niveau de confiance et à une mesure de sévérité d'impact sur l'environnement établi.

Bien que des processus détaillés ou les différents états d'emplacement soient adressés, les issues générales de processus-réponse ne sont toujours pas comprise bonne ou recherché - un problème aggravé par communication faible dans ce domaine multidisciplinaire. Un réseau EPSRC-placé vise à adresser ceci en rassemblant des universitaires, des agences de R&D, des dépositaires, des conseillers et des spécialistes en climat pour synthétiser la connaissance dans le large domaine des prévisions d'impact de changement de climat pour des pentes (réseau de CLIFFS). L'utilité potentielle de ce réseau sera accentuée en cet article par des discussions des impacts d'instabilité de pente sur l'environnement établi, un sommaire des scénarios de changement de climat et une analyse des défis faisant face à ceux impliqués dans la planification, concevant et surveillant des pentes, y compris des issues de risque communiquant et l'incertitude des prévisions de l'instabilité de pente.

**Keywords:** climate change, landslides, risk assessment

## INTRODUCTION

Slope instability of both natural and constructed slopes presently has a significant impact on the built environment and infrastructure in the UK. The topography, geology, present and past climatic conditions and human modification of the landscape result in slope processes being active over a significant area of the UK (Figure 1). Many tens of thousands of people live with continuing slope instability or the threat of instability. This includes many population centres on actively eroding coasts (e.g. Ventnor, Lyme Regis, Holderness) and on inland slopes (e.g. London, Edinburgh, South Wales Coalfield). Tens of thousands of kilometres of transport links and utilities are located in areas susceptible to failure of natural slopes. In addition, construction often involves the formation of cut and fill slopes that can also become unstable. Slope instability can have a major detrimental effect on the UK's infrastructure as demonstrated by the disruption of the road and rail networks resulting from the many slope failures that occurred during the period of high precipitation in winter 2000/2001.

Climate change will have important consequences for the activity of mass movement processes on slopes. Groundwater pressures form a major controlling factor for the stability of soil and rock slopes and their magnitude and distribution, which vary both spatially and temporally, are dependent upon climate. Climate change models predict increasing changes to seasonal and inter-annual variations in precipitation and temperature during the next 100 years. As a consequence, the evapotranspiration-precipitation balance will change. This will affect the hydrological environment governing the majority of mass movements in the UK through, for example, changes in antecedent pore pressures and alteration of trigger event magnitudes. This, in turn, will lead to a change in the frequency, distribution and mode of landsliding in the UK. Landscape sensitivity, in terms of the degree to which it can cope with these rates of change, should therefore be considered as a consequence of combined changes in the triggers (e.g. precipitation events) and preparatory factors (e.g. the antecedent groundwater conditions). It is clear that climate change will significantly modify these and other controlling variables (such as land-use, vegetation cover and soil water chemistry).

**Figure 1.** British Geological Survey map showing the distribution of landslide potential in the UK showing landslide potential in three classes; significant, moderate and low to nil (NERC copyright: Jackson, 2004).

To date, the majority of studies have assessed the consequences for triggering first-time landslides at individual sites (both natural and constructed). More focused generic research has recently started. These include the CRANIUM project (Climate change Risk Assessment New Impact and Uncertainty Methods; see for example www.ncl.ac.uk/cranium) focusing on analysing uncertainty and making robust risk-based decisions for infrastructure design and management in the face of climate change; and the BIONICS embankment project (biological and engineering impacts of climate change on slopes; see for example www.ncl.ac.uk/bionics). However, the general process-response issues are still not well understood. This problem is exacerbated by poor communication between groups involved in research, consultancy and the stakeholders.

A recent document detailing the potential impacts on the UK built environment was published during the summer of 2005 (Vivian *et al.* 2005). It sets out the range of issues that the built environment will be subject to due to processes that are driven by climate change. These are:

- Delay to construction programmes
- Poorer internal environments
- Subsidence and heave
- Slope instability
- Damage to fabrics of buildings
- Structural damage due to wind loading
- Effect on roof drainage

The report gives a clear indication that at present the UK construction industry is generally not implementing any strategies that could result in adaptation of mitigation measures to reduce the potential impacts. It therefore aims to provide guidance for construction professionals to aid them in formulating risk management strategies in this changing climate. The issue of slope stability receives some, but relatively little, attention in this report. It is argued that prolonged and heave rainfall during the winter months is likely to increase the incidence of landslides in the UK, mainly affecting areas that are unstable already. The main mechanisms generating slope instability are considered to be related to the external and internal hydrologies of slopes. An interesting additional point for consideration is that made by Beazant (2003 referenced in Vivian *et al.* 2005) who indicates that the use of absorbent materials in construction may be affected by prolonged wet weather spells making the construction process more expensive by either prolonging the construction period, or forcing the use of more expensive less absorbent (soil) materials.

# OVERVIEW OF CLIMATE CHANGE IN THE UK

Carbon dioxide levels in the atmosphere have risen by over 30% since the industrial revolution. Global average temperatures rose by 0.6°C during the 20th century. The Intergovernmental Panel on Climate Change (IPCC) concluded in 2001 that "most of the warming observed over the last 50 years is likely to be attributable to human activities" (IPCC, 2001). How climate changes in the future will depend on current and future emissions of greenhouse gases and other pollutants, which in turn depend on how population, economies, technology and societies develop (Hulme et al., 2002).

The UKCIP02 climate change scenarios for the United Kingdom were produced by the Meteorological Office's Hadley Centre and the Tyndall Centre for Climate Change Research, with funding from the Department for Environment, Food and Rural Affairs (Defra), in 2002. They described expected climate changes in the UK over the 21st century for four different greenhouse gas emissions scenarios and three time slices centred on the 2020s, 2050s and 2080s. A new set of probabilistic future climate information is currently being developed by the Hadley Centre and will be published by UKCIP in 2008. For a full description of the UKCIP02 scenarios see Hulme et al. (2002).

According to the UKCIP02 scenarios it is expected that the UK will experience:

Higher temperatures (see Figure 2), with regional and seasonal variation:
- by the 2020s: annual warming of between 0.5°C and 1.5°C depending on region and scenario;
- by the 2050s: annual warming of between 0.5°C and 3.0°C depending on region and scenario;
- greater summer warming in the south east than the north west of the UK;
- greater warming in summer and autumn than in winter and spring;
- very high summer temperatures occur more frequently, and very cold winters become increasingly rare; and
- daily maximum temperatures as high as 40°C could be experienced in the south east by the 2080s.

Changing patterns of precipitation (see Figure 3):
- wetter winters, by up to 15% by the 2020s and up to 25% by the 2050s, for some regions and scenarios;
- possibly drier summers, by up to 20% by the 2020s and up to 40% by the 2050s, for some regions;
- heavy winter downpours could occur twice as frequently by the 2080s; and
- significant decreases in snowfall.

Changes in sea level:
- a rise in global average sea level, due mainly to thermal expansion of ocean water and melting of mountain glaciers, in the range of 40 to 140 mm by the 2020s and 70 to 360 mm by the 2050s, depending on the emissions scenario;
- historic trends in vertical land movements will introduce significant regional differences in relative sea level rise around the UK, with much of southern Britain sinking and much of northern Britain rising relative to the sea; and
- extremes of sea level - storm surges and large waves - are expected to increase in height and frequency.

Changes in other variables:
- cloud cover decreasing in spring, summer and autumn; summer cloud cover may decrease by as much as 18% by the 2080s;
- average winter wind speeds along the south coast of the UK may increase by as much as 10% by the 2080s, though this is very uncertain;
- the number of storms each winter crossing the UK could increase from five (the 1961-90 average) to eight by the 2080s (again, this is very uncertain); and
- soil moisture in summer and autumn to reduce significantly across the UK, with the largest reductions - between 20% and 50% by the 2080s - in the south and east.

Some of these changes are already being felt. The 1990s was the warmest decade in central England since records began in the 1660s, and UK coastal waters have also warmed (Hulme et al., 2002). As a result:

- the growing season for plants in central England has lengthened by about one month since 1900;
- heat waves have become more frequent in summer, while there are now fewer frosts and winter cold spells;
- winters over the last 200 years have become much wetter relative to summers throughout the UK;
- a larger proportion of winter precipitation (rain and snow) now falls on heavy rainfall days than was the case 50 years ago; and
- after adjusting for natural land movements, the average sea level around the UK is now about 100 mm higher than it was in 1900.

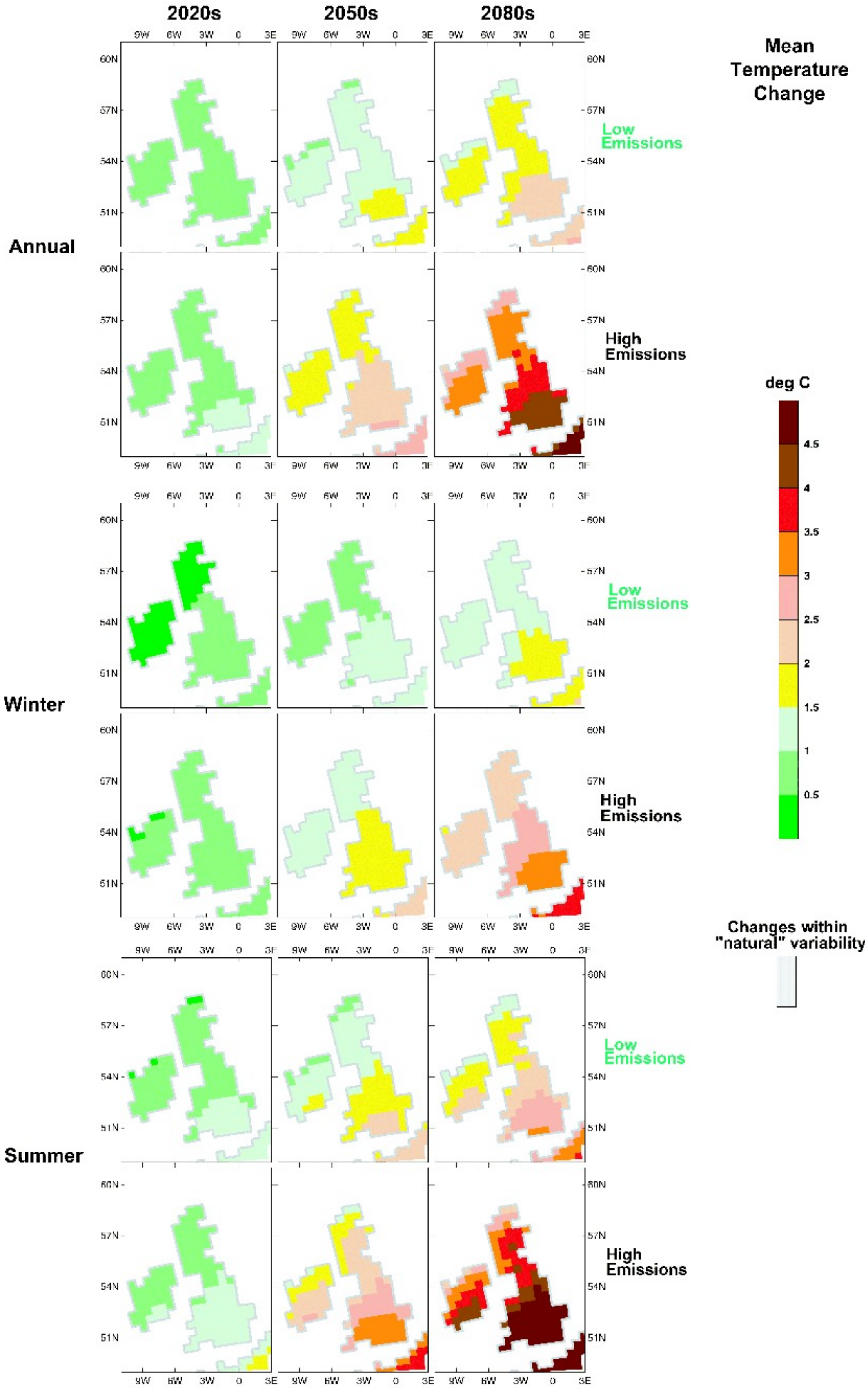


**Figure 2.** Regional differentiation of UKCIP02 scenario outcomes: mean average temperature changes for two emission scenarios shown in three time slices – the 2020s, 2050s and 2080s.

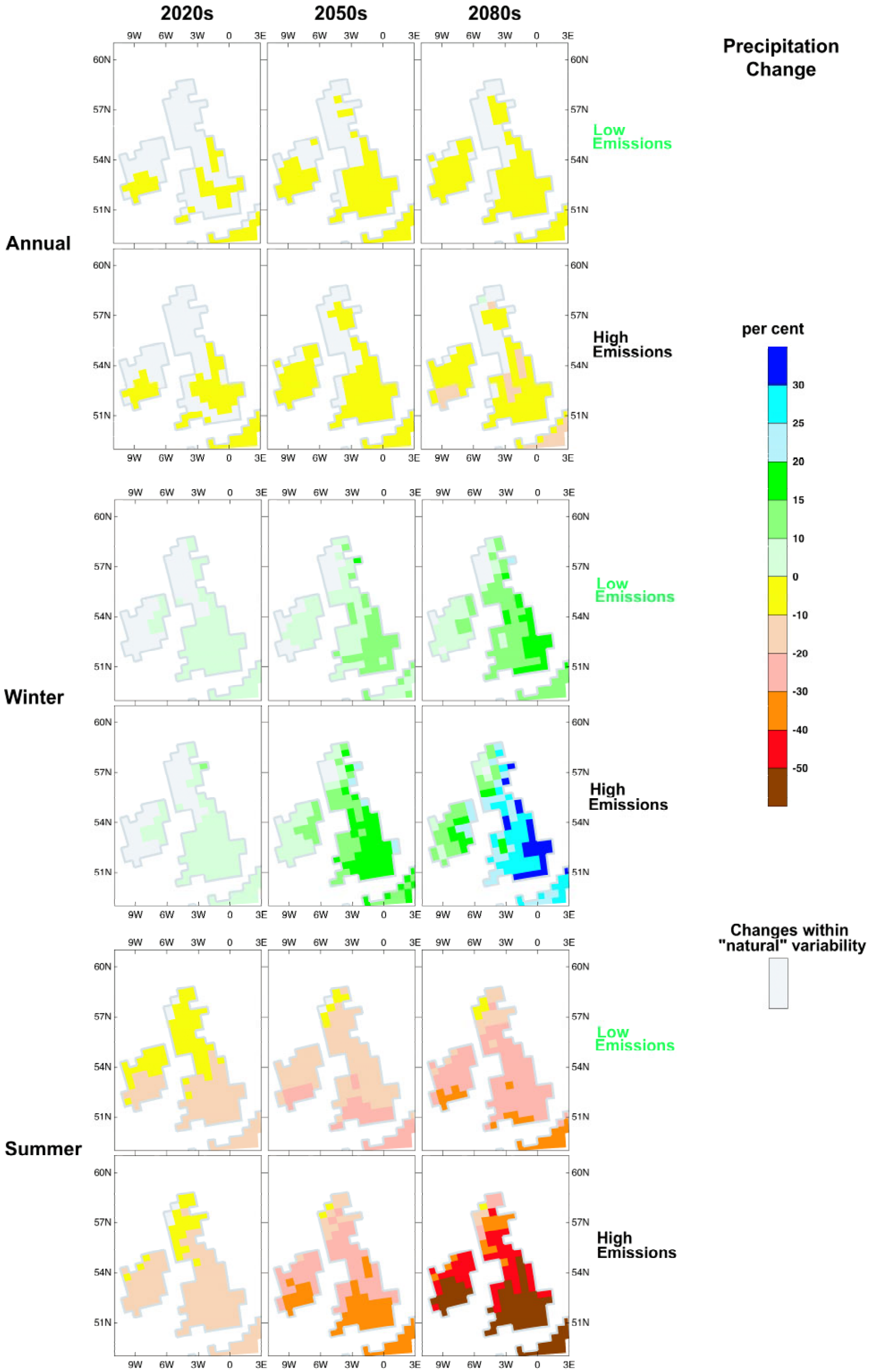


**Figure 3.** Regional differentiation of UKCIP02 scenario outcomes: precipitation changes for two emission scenarios shown in three time slices – the 2020s, 2050s and 2080s.

# CLIMATE CHANGE, SLOPE STABILITY AND THE BUILT ENVIRONMENT

## *Improving forecasting capabilities*

At present, planning and design involving assessments of slope stability often take place based on relatively static information (represented by maps, soil parameters, hydrological models, etc.). At the detailed design stage of a project, slope stability assessment is carried out using past records of groundwater levels and/or measurements made during a site investigation (often over a limited time period). These assessments of stability are valid only as long as the conditions are relevant (i.e. a steady state is assumed). However, changes in dominant input parameters (such as precipitation and temperature shown in Figures 2 and 3 and their resultant impact on, for example, soil water balances) are now clearly occurring at a rate that make it questionable whether steady state information is relevant at best or misleading at worst, certainly when considering that the time period over which designs and land use decisions are being used can readily exceed 50 years (for example, 60 years for Highway Agency earthworks and 120 years for Network Rail).

A range of forecast scenarios of slope instability and distribution are needed that tie in more closely with the forecasted changes in climate variables such as those described in the scenarios above. This, in turn, should lead to the formulation of slope development scenarios where each scenario would be associated with a certain level of confidence and a measure of severity of impact on the built environment.

These forecast scenarios of slope instability and distribution must be communicated as widely as possible to make stakeholders and the general public aware of the scientifically feasible refinements in confidence level and potential societal impact. This approach should cover both constructed (cuttings and embankments) and natural slopes (inland and coastal). Improved understanding of slope dynamics under changing climate conditions will assist the development of appropriate engineering solutions and construction guidelines for the economic design and the optimum management of constructed and natural slopes.

Some excellent recent work on general landslide risk assessment has been described by Lee & Jones (2004), and examples of regional assessments of slope instability have been produced by TRL Scotland and the British Geological Survey (see, for example, Winter *et al.* 2005). However, there is a need to further the discussion of the philosophical basis of existing forecast approaches in relation to landslides. This is an element of the analysis that appears to reside quite well with the geomorphologists/geologists, but less so within civil engineering. Conversely the solution driven nature of a civil engineering approach could do well to focus question-based approaches in other fields. By bringing together these various disciplines a useful element of cross-fertilisation could be generated benefiting both the drafting of research questions and the formulation of practical guidelines.

### *There is no steady state*

παντα ρει και ουδεν μενει

– Heraclitus (500BC)

Impacts of changes in local or regional climate combined with the consequences of land use changes has particular relevance for the assessment and forecasting of mass movement occurrences and intensities. Particularly, the 'understanding and refining of uncertainty' still requires further study. In this context awareness of change and uncertainty forms an extremely important issue. This is currently being addressed for those climate change scenarios focusing on direct hydrological and atmospheric processes. However, key earth surface process-response modes are not yet fully understood and appreciated. The community has an important role to play in the further study of the impact that these processes will have on built environment. This is likely to lead to improved confidence levels of forecasting change and, in turn, can be used to generate greater awareness of the potential risk to society.

Assessments in terms of, for example, distribution of slope instability or forecasts of mass movement activity will be affected by the nature of the analyses. Therefore, it is necessary to establish the validity of basic assumptions of slope process activity and development. Critical comparison of outcomes of steady state models with other approaches such as those offered by non-linear (metastable) dynamic systems may provide enhanced insight into the confidence levels of forecasts of mass movement activity and distribution.

The activity of mass movements in response to climate change may be evaluated in terms of first-time failure and frequency of re-activation triggered by, for example, precipitation events. Trigger event distributions should be analysed in a context of the long-term activity of preparatory processes that affect local slope instability thresholds, but also the frequency and distribution of high-intensity trigger mechanisms must be evaluated. The sequence and relative intensities of preparatory and triggering events are important for the analysis of the likely development of metastable landscapes. In these landscapes, triggers may generate form responses that significantly alter its susceptibility to future disturbances. The landscape is less likely, therefore, to be in the same state at either side of the trigger threshold transgression. It is important, therefore, to evaluate the forecast potential of using a non-linear dynamic equilibrium approach rather than models based on steady state assumptions.

One way of progressing this could be through the further development of the National Landslide Hazard Assessment (NHLA) for landslide hazard zonation (Winter *et al*. 2005). It uses a wide range of data in a flexible way that enables adaptation of the modelling to particular conditions. Winter (*et al*. 2005) suggested that this approach could be useful for short-term management of potentially unstable sites when combined with storm track data from the Meteorological Office. These kinds of models could also form the basis for the development of landslide distribution maps using climate change forecasts as additional input, generating distribution maps similar to those shown for temperature and precipitation (Figures 2 and 3).

## CLIFFS – THE ROLE OF NETWORKING

To achieve a better insight into the links between climate change and slope stability in the UK there is a requirement to determine the information needs and, secondly, and to focus research efforts on targeted assessments of long-term scenarios. The UK Engineering and Physical Science Research Council (EPSRC) has provided funds to establish a broad network that aims to address these issues by bringing together academics, research and development agencies, stakeholders, consultants and climate specialists to synthesise knowledge in the broad field of Climate Change Impact Forecasting For Slopes (CLIFFS network). This is a multi-disciplinary community involving civil engineers (including specialists from diverse fields such as geotechnics, structural design and transport engineering), geomorphologists, hydrologists, geologists, climatologists, statisticians, insurance experts, etc. The network is managed from a base at Loughborough University and is supported by a large core group (see Table 1). It is very much a stakeholder driven network relying on active inputs from its core group and members.

It has been recognised widely that the UK will have to adapt to climate change. This change will take place even if global emissions were to be reduced with immediate effect. It has also been recognised for some time that the adaptation needs to take place in a staged and prioritised fashion (see for example the earlier DETR - Climate Change: Draft UK Programme, Section III, Adapting to the impacts of climate change in the UK, and more recent CIRIA report on the outcomes of RP668 Climate change risks to building (Vivian *et al*. 2005)). The network aims to identify the priorities for the case of slope instability.

**Table 1.** Core members of ***CLIFFS***

| ***CLIFFS core group*** | |
|---|---|
| British Geological Survey | British Waterways |
| Cementation Foundations Skanska Ltd | Geotechnical Consulting Group |
| British Geotechnical Association | Halcrow Group Ltd |
| Highways Agency | Imperial College London |
| Isle of Wight Council | Kingston University |
| Loughborough University | Mott MacDonald |
| Nottingham Trent University | Queen's University Belfast |
| UK Climate Impacts Programme | University of Bristol |
| University of Birmingham | University of Newcastle |

The network aims to stimulate an integrated research response to address the intricately linked problem of forecasting, monitoring, design, management and remediation of climate change induced variations in slope instability. The size of the task and the complexity and multi-disciplinary nature of the problem requires active participation of a wide group to assess the magnitude of the resulting impact on UK society and to identify appropriate management and remediation strategies. To achieve this, the network will bring together a broad range of relevant academics and industrialists to synthesise knowledge, to agree a prioritised set of research needs, to seek funding for this research, and to disseminate the outcomes as widely as possible. The CLIFFS network falls within the EPSRC prioritised area of *Infrastructure and Environment* and specifically it contributes to the themes of *Engineering for Adaptation to Climate Change* and *Engineering and Science for Sustainability*. The network is maintained through a series of activities that include themed workshops, an international symposium and a wide range of dissemination activities including a designated web site (cliffs.lboro.ac.uk).

The organisation of themed workshops addressing specific aspects forms the main activity of the network. These workshops will allow the sharing of expertise and ideas and are used to focus and prioritise research, construct appropriate research teams and develop proposals. They are also used to keep stakeholders informed, obtain guidance from them on priorities and address specific issues raised by the end user community. These issues include:

- Use of climate change information in slope stability assessments including uncertainty and risk assessment,
- Validation of groundwater models incorporating climate forecast scenarios,
- Impact of climate change on the magnitude and frequency of cutting and embankment slope failures,
- Impact of climate change on the magnitude and frequency of first-time failures and re-activated failures in natural slopes,
- Impact of climate change on the magnitude and frequency of failures in coastal slopes,
- Influence of vegetation on slope stability,
- Monitoring techniques and applications,
- Development of appropriate remediation strategies,
- Strategies for presenting and using information on future slope instability, including landside hazard susceptibility maps related to climate change scenarios, issues of land use/planning and slope design implications.

## CONCLUDING REMARKS

It is generally acknowledged that climate change will have important consequences for the activity and distribution of events capable of affecting the stability of slopes and the triggering of mass movements. At many different levels these issues are being addressed, but because of the multi-disciplinary nature of the problem, communication remains an issue requiring improvement. Networking provides opportunities for developing effective research and information exchange for the wider communities dealing with, or affected by, slope instability in the built environment. It is imperative that an integrative and inclusive approach is established to ensure that our insights are communicated more effectively, because of the cost implications involved.

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