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Impact of predicted climate change on landslide reactivation: case study of Mam Tor, UK

Abstract Global change is expected to result in worldwide increases in temperature and alteration of rainfall patterns. Such changes have the potential to modify stability of slopes, both natural and constructed. This paper discusses the potential effect of global climate change on reactivation of landslides through examination of predicted changes in rainfall pattern on the active landslide at Mam Tor, Derbyshire, UK. This landslide is of Pleistocene origin and is crossed by a road that is now abandoned. Damaging winter movement is known to occur when precipitation reaches both 1-month triggering and 6-month antecedent thresholds. Return periods for threshold exceedence is modelled statistically, and the climate change data from the UKCIP 2002 report (Hulme et al. 2002) is applied to this model. For the predicted changes in precipitation, it is shown that the instability threshold could decrease from 4 to 3.5 years by the 2080s for the medium–high climate change scenario. However, predicted temperature changes could influence the response of the landslide through increased evapotranspiration leading to a change in the triggering precipitation thresholds, and this will help counter the impact of changes in precipitation. Analysis of sources of uncertainty in the model has been used to establish the factors that contribute to the predicted changes in stability. Assessment of these factors can provide an indication of the potential impact of climate change on landslides in other areas of the UK.

Introduction

Over the next 100 years, global climate change, believed to be caused by a build-up of green house gases, is predicted to cause temperatures to rise worldwide. This will lead to alteration of intensity and quantity of precipitation. In the UK, such changes could lead to problems with increased flooding, droughts and slope instability, as highlighted in a UK Government report based on the latest climate change predictions produced jointly by the Tyndall Centre for Climate Change Research and Hadley Centre for Climate Prediction and Research (Hulme et al. 2002). Groundwater pressures are a controlling factor for the stability of soil and rock slopes, and their magnitude and distribution, which vary both in space and time, are dependent upon climate. Climate change models have predicted an increasing rate of change of seasonal and inter-annual variations in precipitation and temperature across the UK (Hulme et al. 2002).

As a consequence, the evapotranspiration–precipitation balance will change. This will affect the hydrological environments governing slope instability through, for example, changes in antecedent pore pressures and alteration of trigger event magnitudes. This in turn could lead to a change in the frequency, distribution and mode of landsliding. 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 could significantly modify these and other controlling variables (e.g. vegetation). Knowledge is required on how predicted climate change could modify the frequency and magnitude of slope instability events so that impact on the built environment can be assessed and remediation strategies developed.

Relationships between rainfall patterns and slope instability are reported in the literature for a range of slope failure mechanisms (e.g. shallow and deep-seated first-time slides and reactivated movements) and climates. Chowdhury and Flentje (2002), Corominas and Mayo (1999) and Fiorillo and Guadagno (2000) report recent studies on both historical and current behavior. Examples of studies into the potential impact of climate change on slope instability have been reported by Dehn et al. (2000) for the Alvera mudslide in the Italian Dolomites, van Beek (2002) for the Alcoy region of Spain and Collison et al. (2000) for the Roughs landslide near Hythe in Kent, southeast England. These studies demonstrate the applicability of the general approach presented in this paper and confirm the importance of considering the likely impact of future climate change on slope instability. However, trigger and antecedent rainfall thresholds are highly site-, region- and material-specific and therefore it is not possible to use studies reported in the literature as a guide to future behaviour of other landslides in regions that experience different climates.

Geology of the UK is extremely varied, with rocks of ages ranging from Pre-Cambrian to Quaternary, and with representations of all eras. In the Southeast are the younger gently folded sedimentary rocks forming undulating landscapes. Progressing in a northwest direction, the rocks at outcrop become older. In Wales and Scotland are highlands formed from the oldest metamorphic rocks of varying grades. Igneous rocks are present in the southwest and northwest with both intrusive and extrusive present. Overall, the variations in geology are considerable and complex due to the long geological history of the UK. The UK has a temperate climate with precipitation in the order of 800 mm per annum (southeast) to 1,500 mm (northwest) and summer/winter temperatures typically ranging from 25 to −5°C, respectively, with the higher temperatures in the south and lower in the north. The climate is complex with extremes of both temperature and precipitation.

This paper considers future instability of a reactivated landslide in a natural slope. First-time slope failures in inland areas are rare in the UK; however, there are many pre-existing slides that are vulnerable to reactivation. The main trigger of instability is increases in ground water level. Reactivated movements are

Fig. 1 Photograph of the Mam Tor landslide showing the upper and lower roads crossing the slide and displaced down slope


typically slow and hence rarely threaten life, but they can be destructive to property and infrastructure, and are therefore costly.

This paper discusses the potential effect of climate change on the instability of such inland slopes through examination of the impact of predicted future rainfall patterns on an active landslide at Mam Tor, Derbyshire, UK (Fig. 1), which historically has been shown to be sensitive to rainfall trends. This study uses a rainfall threshold analysis model that examines the impact of predicted changes in precipitation. A brief discussion of the impact of predicted changes in temperature is also included. The aim is to use a relatively simple approach combining existing information on precipitation trigger levels for a landslide and readily available climate change data, and hence to investigate possible general trends in future behaviour. It should be noted that the authors are geotechnical engineers and not climate specialists (i.e. they are end users of climate change data).

Mam Tor landslide

Mam Tor is a hill of Carboniferous sandstones and shales located at the western end of the Hope Valley in Derbyshire. It is located 1.48° W and 53.21° N. The summit and upper slopes of Mam Tor are formed in a sequence of shales, siltstones and fine-grained sandstones that constitute the Mam Tor beds. These overlie shales, mudstones and thin siltstones, known as the Edale Shales. Both of these units dip approximately to the north at 5–15°. The landslide is a kilometre-long feature orientated west to east on the eastern flank of the Mam Tor hill. The initial slope failure occurred more than 4,000 years ago as a rotational landslide that developed into a large debris slide at its toe. A plan of the landslide is shown in Fig. 2 and the cross-section A–B marked on the plan is shown in Fig. 3. A road was built across the landslide nearly 200 years ago and this provides clear evidence of continuing movement of the slide mass through the existence of multiple layers of bitumen used in repairs (Fig. 4).

Fig. 2 Map of the Mam Tor landslide and adjacent features (after Waltham and Dixon 2000). The *inset* shows the location of the site in the UK. The road crosses the middle of the slide mass twice, orientated approximately north–south, and is shown in the position occupied in 1996. *Arrows* show the direction of movements. *Figures* by the boreholes indicate depths in metres to the slip surface. Cross section A–B is shown in in Fig. 3
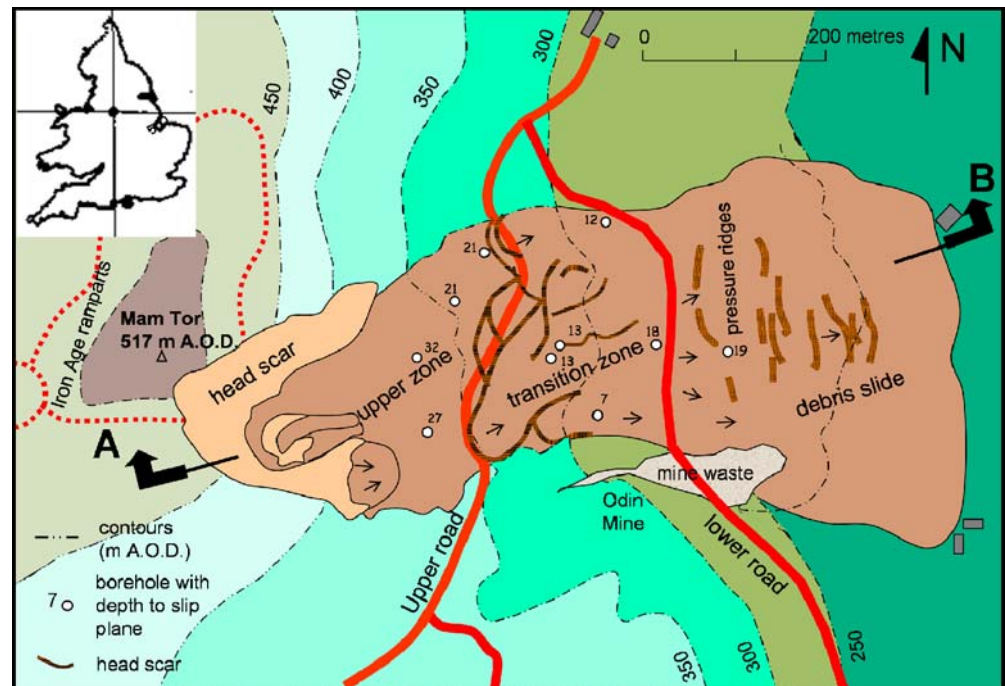
Fig. 3 Cross-section A–B through the Mam Tor landslide along the line indicated on Fig. 2 (after Waltham and Dixon 2000)
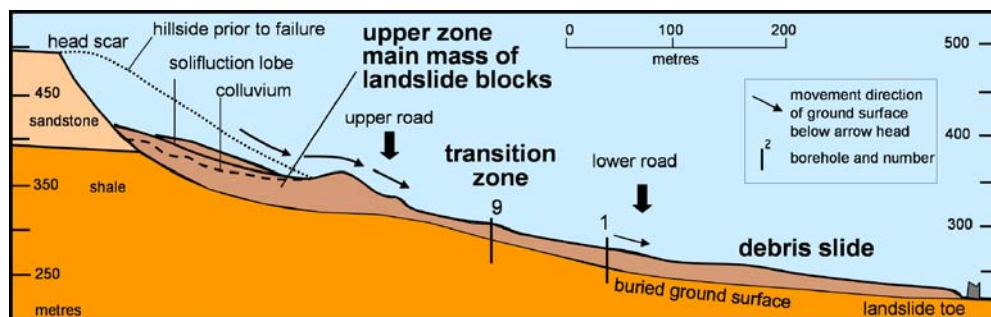
A comprehensive study of the landslide was reported by Skempton et al. (1989). This included a detailed subsurface investigation, testing and analysis of stability. The slide mass can be divided into an upper zone within the bounds of the original hillside, a transition zone consisting of a complex of slide blocks, and a translational slide below this (Figs. 2 and 3). Movements in the transitional zone currently average 0.25–0.5 m per year, and instability in this area causes movements in the rest of the slide. The road, shown on Figs. 1, 2 and 4, was closed in 1979 due to significant movements and excessive maintenance costs. Records of road repair dating back nearly a century provide a history of the landslide's movements.


Fig. 4 Photograph of a section of the upper road showing multiple phases of road repair, and movements that have occurred since the road was closed in 1979

Waltham and Dixon (2000) used detailed movement surveys carried out over an 8-year period, in conjunction with the historical movement records and information reported by Skempton et al. (1989), to propose rainfall thresholds. These thresholds relate to cumulative amounts of rainfall occurring over a certain period of time, which result in significant movement of the landslide as indicated by the records of road disruption. They correlated rainfall data from a nearby weather station with the landslide movement records, and found that instances of damaging movement are related to both 1-month triggering and 6-month antecedent rainfall thresholds being exceeded. They concluded that significant movement in any month from October to February could be triggered by precipitation of 210 mm over the preceding month, combined with 750 mm over the preceding 6 months. Figure 5 shows the correlation of rainfall patterns and landslide movements in the period 1903 to 1998.

Significant movements of the landslide occurred as a consequence of 20 out of the 23 events when both rainfall thresholds were exceeded. Movements were also notable on four other occasions in marginally drier winters, and there are 7 years when landslide movements appear not to conform to the proposed rainfall thresholds. Instances where the proposed rainfall thresholds do not correlate with observed movements could be a function of rainfall patterns for Mam Tor at times being different from those recorded at the weather station and used in this study, as indicated by Rutter et al. (2003). It should be noted that temperature, and hence evapotranspiration, was not considered in the Waltham and Dixon (2000) study. In the period 1903 to 1998 significant slide movements occurred on average every 4 years, and this is a function of the rainfall patterns (Waltham and Dixon 2000). Deformation monitoring of Mam Tor reported for the period 1996 to 2002 by Rutter et al. (2003) confirms the above behaviour.

Although there are some instances when exceedence of the thresholds and landslide movements do not correlate, the proposed rainfall thresholds provide a simple approach for relating the stability of this complex slide mass to rainfall history. A preferable deterministic approach would be to monitor the response of pore water pressures on the slip surface to rainfall and temperature histories, to calculate stability and relate it to measured movements. However, for this site, like for the vast majority of landslides, there is no history of extended pore pressure and direct deformation monitoring, and hence no data that can be used in a coupled climate/groundwater/stability model. Due to the lack of such data, a simple probabilistic approach has been employed using thresholds to investigate the control of rainfall on past stability and hence to examine the possible consequence of predicted changes in rainfall distributions on the frequency of future instability.

Fig. 5 Plot of maximum 1- and 6-month rainfalls recorded in each year during 1903–1998 and correlation with recorded landslide movements (after Waltham and Dixon 2000). Years with the rainfall *bars* in *blue* are those where both the 1- and 6-month threshold levels were exceeded and landslide movement was recorded. Years with *green* rainfall *bars* did not have the proposed correlation between rainfall and landslide movements
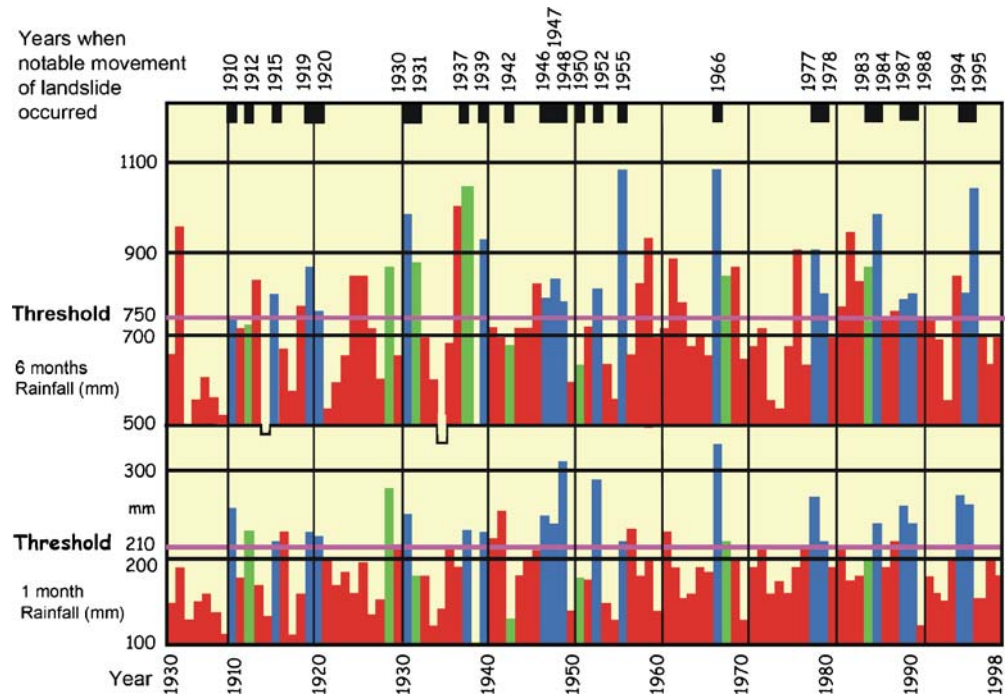
Predicted climate change

Climate change model

To investigate the potential effects of global change, the UK government set up the Climates Impacts Program (UKCIP) in 1997. The most recent climate change prediction information is summarised in the UKCIP 2002 report (Hulme et al. 2002). This report is openly available to the public and the UKCIP 2002 Scenario data files for precipitation and temperature are freely available to researchers. UKCIP 2002 uses HadCM3 as its base model, the results of which have been downscaled to a 50-km resolution using nested local area models. UKCIP predicted values are based on data from the 1961–1990 period. The model was validated against the known climate during 1961 to 1990 and future values of temperature and rainfall are obtained by applying the predicted changes to the mean values over the 1961–1990 period.
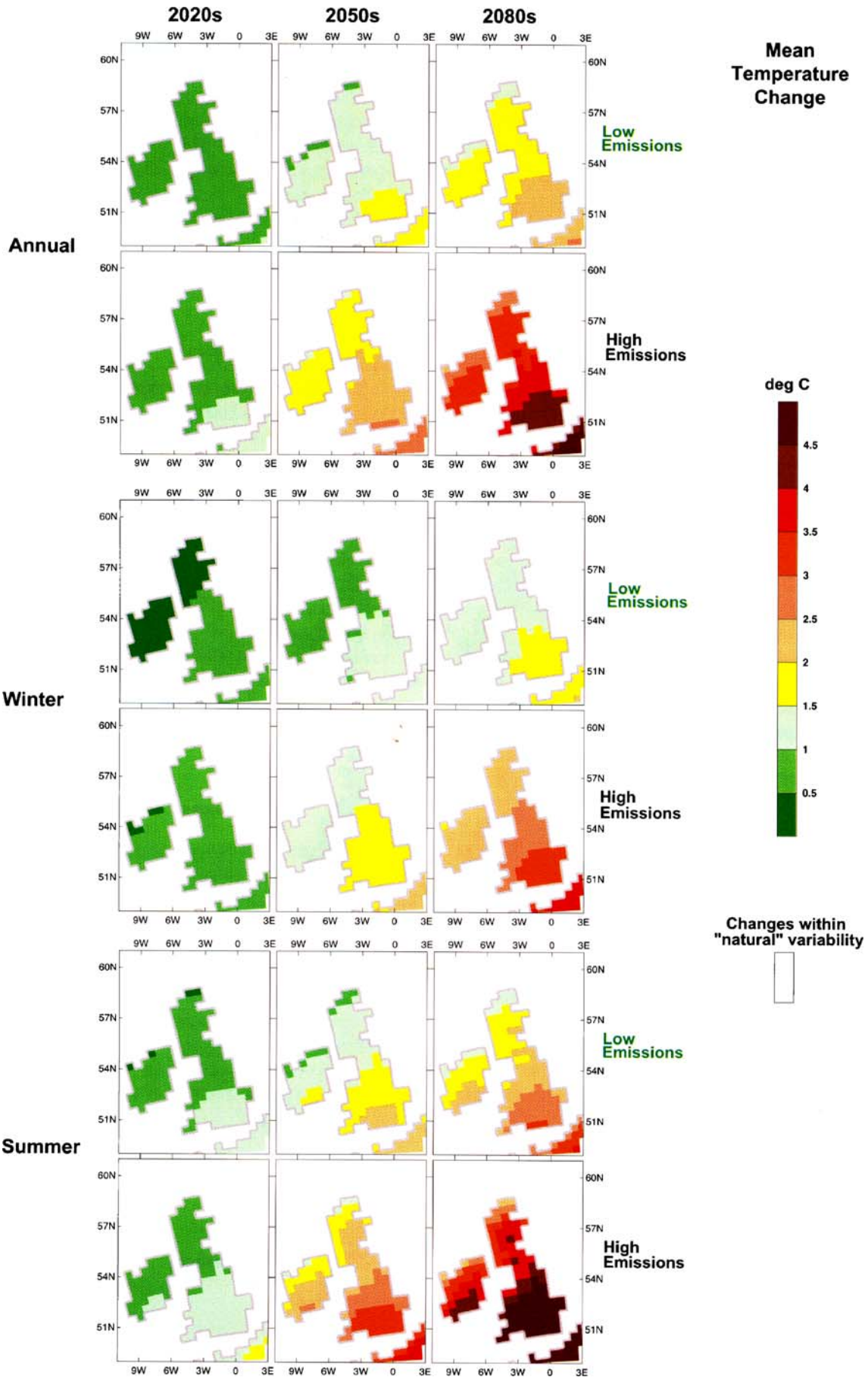
Predictions have been produced for the 2020s, 2050s and 2080s and for four different greenhouse gas emission scenarios at each time period, defined as low (L), medium-low (ML), medium-high (MH) and high (H). It should be noted that there is currently no information available on the relative probability of these scenarios occurring. UKCIP 2002 predicts the following general UK climate trends for the next 80 years: average annual temperatures will rise between 2 and 3.5°C, with the largest increases in the south and east of the UK, and most of the warming being in summer and autumn. Precipitation is expected to decrease by 0 to 15%, although winters are expected to be wetter. Figures 6 and 7 show the predicted temperature and precipitation changes, respectively, across the UK for the low and high scenarios in the 2020s, 2050s and 2080s. Extremes of temperature in summer and precipitation in winter are expected to increase. Soil moisture content is expected to fall dramatically in the summer months and increase slightly in winter, with a gradient from the south east to the northwest of the UK.
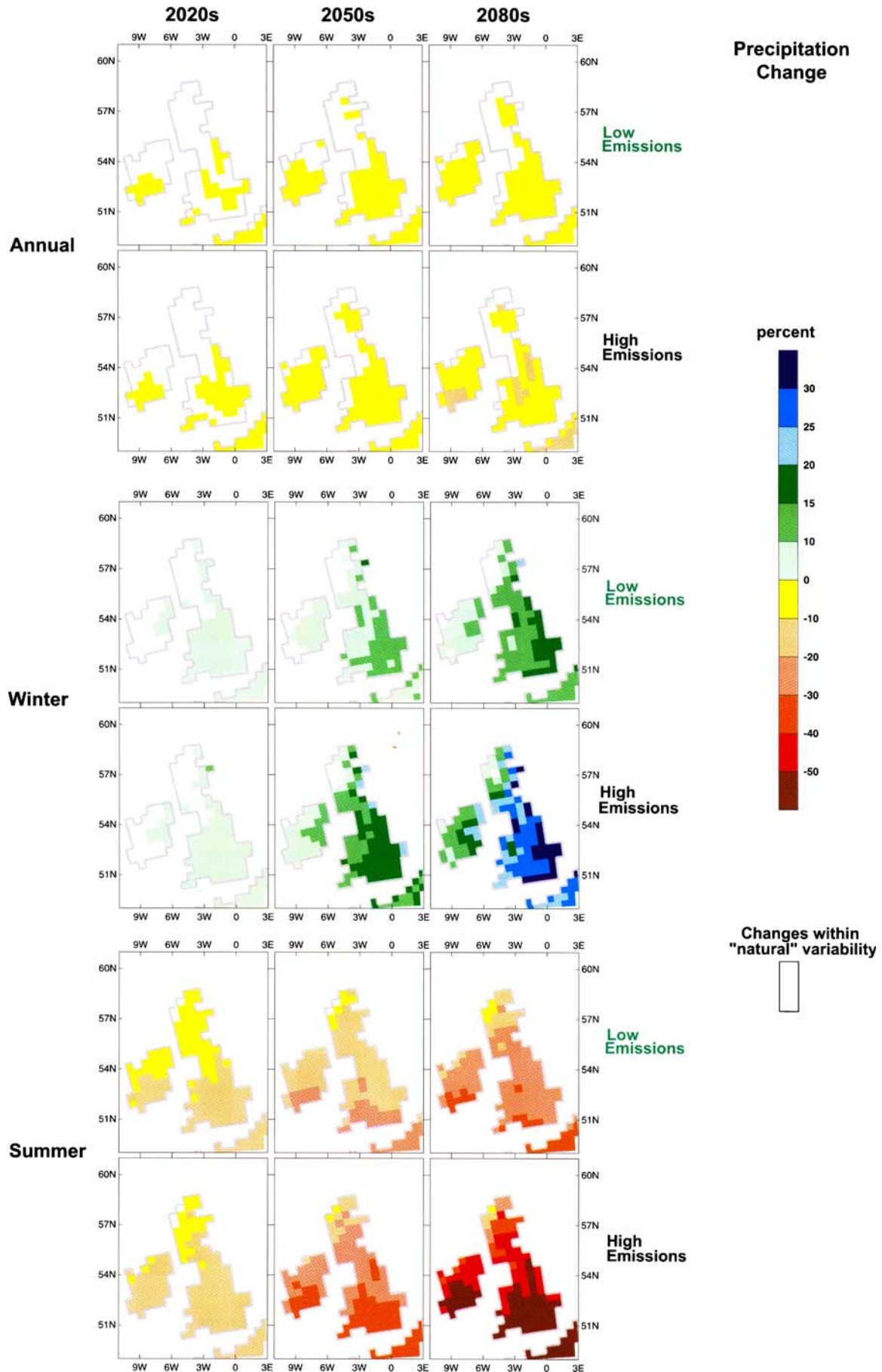
Uncertainty in predictions

Values for potential errors and uncertainty in the modelling are given in the UKCIP 2002 report (Hulme et al. 2002); however, no indication of likely probability is provided. Comparison of HadCM3 with other global circulation models of Western Europe suggests that the approach taken is consistent. It gives temperatures and winter rainfall values that are in the centre of predicted values from the other models; however, it predicts a climate that is significantly drier in the summer months than most of the other models. The use of the maximum and minimum predicted values of temperature and rainfall in analyses such as presented in this paper is problematic (i.e. using high or low scenarios). Analyses using these extreme values produce widely differing results (i.e. instability return periods) but with no level of probability or confidence attached to them.

It is planned that the next generation of UKCIP climate change scenarios (UKCIPnext), due to be available in 2008, will contain statistical distributions for key factors such as temperature and precipitation, and this will enable use of the climate data in probabilistic analyses and aid assessment of uncertainty. It should be noted that climate change predictions are inherently uncertain and that there are major research groups around the world studying this problem, including the downscaling of model outputs to local scales. Those involved in the assessment of slope instability already have to deal with uncertainty relating to soil properties and groundwater. Investigating the likely influence of climate change introduces additional uncertainty. At this time it is considered that the simple approach introduced in this paper is valid and useful, and can show general trends. It

Fig. 6 UK temperature changes, annual and seasonal, predicted for the UKCIP low ▶ and high scenarios (Hulme et al. 2002)

Mean Temperature Change

could be used until further information is available allowing more detailed assessment of uncertainty.

Mam Tor predicted climate change data

The historical climate data used in this study have been obtained from a weather station that lies approximately 10 km southwest of Mam Tor. Previous studies by Skempton et al. (1989) and Waltham and Dixon (2000) have commented that values at Mam Tor are likely to be approximately the same as recorded at the station. However, recent rainfall measurements by Rutter et al. (2003) suggest that there may be significant differences over some periods of time. These differences could explain the instances when the observed landslide movements do not match exceedence of the rainfall threshold as discussed above. This study has used predicted monthly changes in mean precipitation (percent change) and monthly changes in inter-annual variability of precipitation (percent change), all of which are obtained directly from the published UKCIP 2002 data.

Table 1 shows the mean monthly precipitation values measured for the 1961–1990 period, and those predicted for the medium-high UKCIP emission scenario in the 2080s for the Mam Tor area. Table 2 shows values of mean monthly standard deviation from the mean monthly totals of precipitation for the same periods. As Mam Tor is located in the centre of the UK, changes in both temperature and precipitation are not extreme compared to predicted changes for other areas of the UK (e.g. southeast and northwest; Hulme et al. 2002).

Rainfall threshold analysis

Methodology

To investigate the future response of the Mam Tor landslide to predicted climate change, a statistical rainfall threshold analysis (RTA model) has been developed, which gives return periods for the exceedence of Waltham and Dixon's (2000) 1- and 6-month thresholds. Climate data from the period 1961–1990 have been used to calculate mean monthly precipitations and standard deviations for the Mam Tor area (Tables 1 and 2). Rainfall patterns for each winter month have been modelled using a Gamma distribution rather than a normal distribution (i.e. shape of rainfall amount vs time graph). A normal distribution, although simple, is considered unsuitable because monthly rainfall data are bounded by zero on one side and skewed on the other (Wilks 1995), and the Gamma distribution better reflects these traits. However, antecedent rainfall has been modelled as a normal distribution because 6-month totals are further from the bounding zero value and skewing is less

pronounced. A maximum monthly value of 300 mm rainfall has been applied so that amounts of rainfall above this do not contribute to the cumulative values. This is an attempt to take account of increased runoff during periods of near-surface ground saturation. The magnitude and implications of applying this cutoff are discussed below.

The probability of the 1-month threshold being exceeded in a particular month has been calculated as follows:

1. Mean precipitation for each month has been calculated for the period 1961–1990.
2. Standard deviation from the mean has been calculated for each month.
3. Probability of exceeding the 1-month threshold of 210 mm has been calculated using a Gamma distribution.

The 6-month rainfall total, and hence threshold, are formed from rainfall in the month that is used to assess exceedence of the 1-month threshold of 210 mm plus the proceeding 5 months of rainfall. Therefore, it must be combined with the 1-month threshold. If this were not done, an exceptionally high amount of rainfall in a trigger month would be ignored and the probability of both thresholds being exceeded would be underestimated. In effect, if the 1-month threshold is exceeded, then there is a greater chance of the 6-month threshold also being exceeded.

The coupling has been achieved by changing the 6-month antecedent rainfall period to 5 months, which is then added to the 1-month triggering rainfall value to give a 6-month total. For instance, if it were assumed that 220 mm rain fell in January then the 6-month threshold would be exceeded if 750−220=530 mm of rain fell in the preceding 5-month period of August to December. This approach results in the 5-month threshold varying with the 1-month threshold, being equal to 750 mm minus the 1-month rainfall. The probability of the 5-month rainfall total exceeding the required threshold can be obtained in exactly the same way as in steps 1 to 3 listed above, but with the individual month data replaced with the 5-month total, and with a normal distribution used in place of a Gamma distribution.

The probability of rainfall in a given month resulting in both thresholds being exceeded is calculated by multiplying the probability of exceeding each of the 1- and 6-month thresholds together. The probability of at least 1 month in any given year exceeding both thresholds is obtained from these individual month probabilities. The reciprocal of this probability is the return period in years of exceeding both thresholds, and hence the return period of major landslide movements occurring.

In the above approach it is assumed that the 1- and 6-month thresholds are independent variables. Mayes (1996) reports that there is little correlation between incidence of wetter winters and

Table 1 Measured mean monthly precipitation totals (mm) for the 1961–1990 period and predicted by Hulme et al. (2002) for the medium–high emission scenario in the 2080s

Period	January	February	March	April	May	June	
1961–1990	140	95	113	88	89	92	
Medium–high scenario 2080s	170	109	119	83	72	63	
Period	July	August	September	October	November	December	Annual Totals
1961–1990	84	104	107	122	132	140	1304
Medium–high scenario 2080s	50	63	79	110	141	165	1224

Table 2 Mean monthly values of standard deviation (mm) from the mean monthly totals of precipitation measured for the 1961–1990 period and predicted by Hulme et al. (2002) for the medium–high emission scenario in the 2080s

Period	January	February	March	April	May	June
1961–1990	54	53	54	43	44	54
Medium–high scenario 2080s	62	60	59	47	48	47
Period	July	August	September	October	November	December
1961–1990	44	42	55	54	49	65
Medium–high scenario 2080s	39	37	58	57	51	73

wetter summers. Therefore, a wet winter month is no more or less likely to be preceded by a wet 6-month antecedent period and, predicted precipitation values for each month can be considered independent. However, it could be argued that as exceedence of the 6-month threshold is influenced by the 1-month value, the values are dependent. Further work is required to investigate the influence of assuming the values are dependent. Figure 8 provides a schematic of the RTA showing the main calculation steps.

The model was validated by calculating the return period for movement of the Mam Tor landslide in the period 1961 to 1990 and comparing the calculated return period with the observed. Using the 1-month rainfall threshold of 210 mm and the 6-month antecedent rainfall threshold of 750 mm the above approach predicted that significant movements would occur on average every 4.0 years. This compares favourably with the observed average return period during 1961 to 1990 of 4.3 years and close to 4 years over the period 1903 to 1990 (Waltham and Dixon 2000). A

Fig. 8 Schematic of the rainfall threshold analysis showing calculation steps

key element of the above analysis is the setting of an upper limit of 300 mm on the 1-month threshold that can contribute to the 6-month total (i.e. to take account of soil saturation and hence runoff). The good agreement between the predicted and observed return periods indicates that this selected upper limit of 300 mm is appropriate. However, improved confidence would be provided by conducting research to obtain site-specific 1-month threshold runoff values.

Changes in precipitation

Changes in precipitation predicted by UKCIP 2002 have been used to adjust the measured mean monthly and standard deviation precipitation values from the period 1961 to 1990. This then allows the average return period for landslide movement to be recalculated for the predicted changes in precipitation. The use of rainfall thresholds based on observation of past behaviour to investigate future instability is based on an assumption that climate change does not alter the basic response of the slope to climate events (i.e. the same thresholds apply in the future). There is currently inadequate information on climate/groundwater/slope movement relationships to confirm the validity of this assumption, although the mechanism of reactivated movements is not expected to change significantly. Measured mean monthly precipitation totals for 1961 to 1990 and predicted values taken from the UKCIP 2002 medium–high scenario are tabulated in Table 1 for the Mam Tor area and these are plotted in Fig. 9. Mean annual precipitation is predicted to fall slightly from 1,304 to 1,224 mm (Table 1); however, the variability of winter precipitation is expected to increase (Table 2). It is therefore likely that there will be a greater incidence of extreme events in the winter months (Hulme et al. 2002).

Future average return periods for exceeding the rainfall thresholds, and hence for landslide movements, are shown in Fig. 10. A drop in the average return period from 4.0 to 3.5 years by the 2080s is predicted for the medium–high climate change scenario. This indicates that wetter winters with more extreme events are likely to counteract lower annual rainfall totals and drier summers. Figure 11 shows the probability of exceeding both the 1- and 6-month thresholds in any given month. From this it can be seen that drier summers and wetter winters shift incidents of exceeding the thresholds, and hence major instability, towards the end of the winter period (i.e. from December to January). Also shown in Fig. 11 are the calculated historical probabilities for a threshold being exceeded in a given month. These have been calculated by dividing the number of observed occurrences of major movement in a given month over the period 1903 to 2002. There is a strong correlation between the historical probabilities and those predicted to occur during the 1961 to 1990 period using the statistical method outlined above. The good agreement provides further confidence in the approach taken.
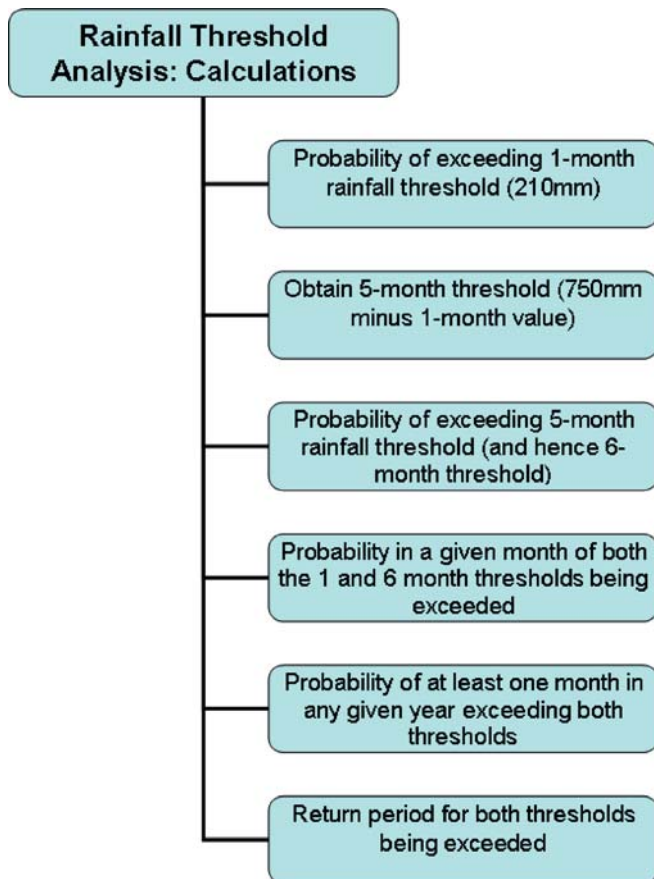
Fig. 9 Mean monthly precipitation values (mm) for the 1960–1991 period, and the medium–high (MH) scenario for the 2020s, 2050s and 2080s
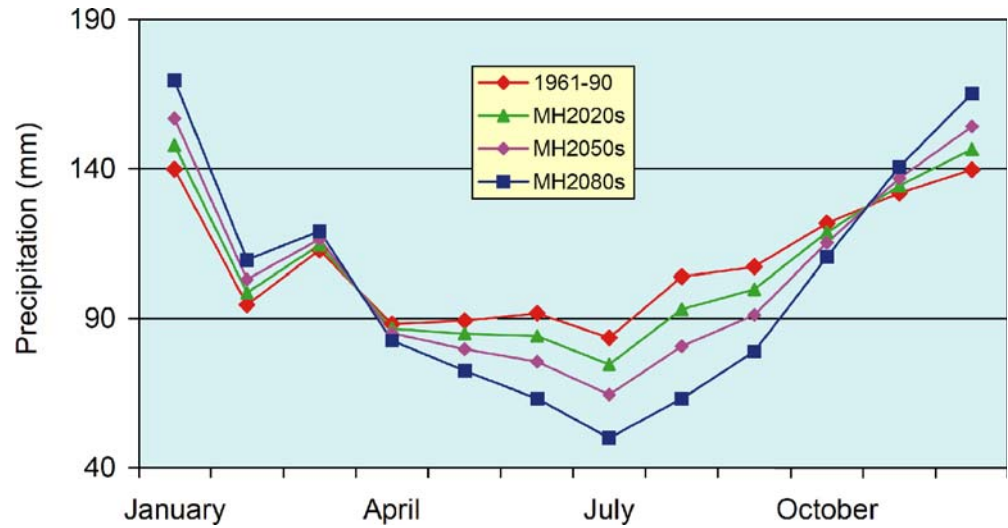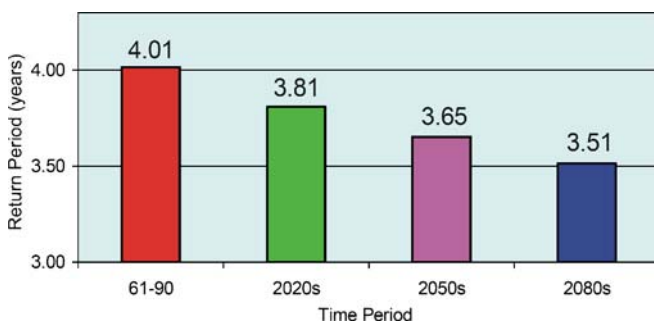
Figure 11 can be used to explain the reason for the predicted reduction in return period for major movement of the landslide. The probabilities of exceeding the thresholds in October and November are significantly reduced by the much drier antecedent periods. The probability of exceeding the thresholds in December remains constant until the 2080s, when the effect of the drier antecedent periods begin to outweigh increased monthly precipitation, and probabilities of landslide movement falls. However, by January, antecedent values are essentially unchanged, and the very large increase in monthly rainfall results in a significant increase in the probability of the rainfall thresholds being exceeded. This analysis shows that the changes predicted by the UKCIP 2002 medium–high scenario are almost balanced, with increased and more variable winter rainfall just outweighing the influence of drier summers.

As annual totals of rainfall are predicted to reduce in the Mam Tor area, it is the increased seasonality and variability of precipitation that gives the predicted increased instability of the landslide (i.e. shorter return periods). It should be noted that changes in precipitation given by UKCIP 2002 are seasonal and not monthly values, and there are currently no estimated errors attached to these data. More detailed information would improve confidence in the results such as the probability data that are to be included in the 2008 UKCIP next data sets.
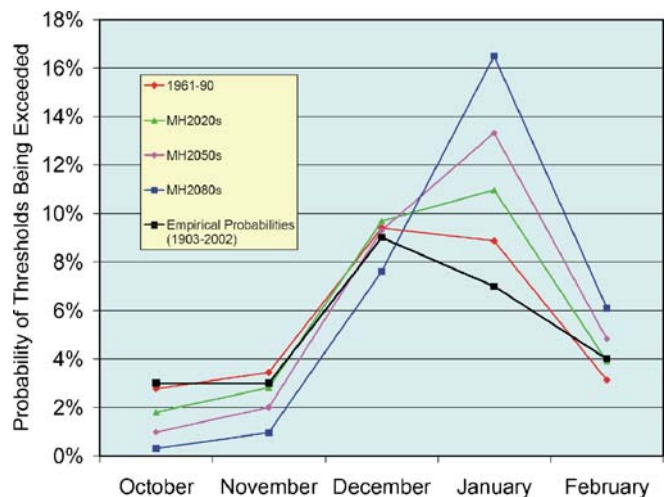
Whilst the medium–high UKCIP scenario has been used for the main detailed analysis, the other three scenarios have also been assessed for comparison, the results of which are shown in Fig. 12. The changes in return period reflect the predicted changes in rainfall regime, with the high scenario giving the largest predicted reductions in return periods as expected. Although there is currently no information on the likely probability of occurrence of the four scenarios (i.e. as this will depend on future global CO_2 emissions and hence on industrial development trends and national mitigation strategies), all scenarios produce a reduction in the predicted return period for landslide movements. It is only the magnitude of the change (linked directly to the scenario) that is uncertain.

Influence of changes in temperature

The RTA model presented above does not include the effect of increases in mean temperature predicted by UKCIP 2002. These are in the order of 2°C in winter and 4°C in summer. Table 3 shows the 1961 to 1990 measured changes in mean monthly temperatures

Fig. 10 Return periods for threshold exceedence (no temperature correction) based on the medium–high scenario

Fig. 11 Calculated probabilities of thresholds being exceeded within any given month for the 1960–1991 period, and the medium–high (MH) scenario for the 2020s, 2050s and 2080s, and empirical probabilities for the 1903–2002 period
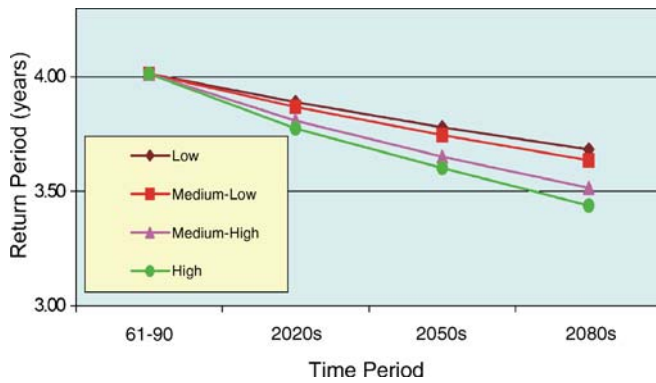
Fig. 12 Return periods of threshold exceedence for the four emission scenarios

and the predictions for the medium–high scenario at Mam Tor. These are likely to result in increased evapotranspiration and greater soil moisture deficits. Buma's (2000) study of an alpine landslide found that an effective rainfall (total rainfall minus evapotranspiration) threshold analysis modelled slope behaviour better than a total rainfall threshold model. However, the precipitation threshold values established by Waltham and Dixon (2000) were total values. They did not consider evapotranspiration and hence effective threshold rainfall values for Mam Tor were not calculated.

Waltham and Dixon (2000) considered temperature effects to be of secondary importance for climatic conditions in the period 1900 to 2000, as the total rainfall threshold values correlated well with observed periods of major movements. It could be argued that new thresholds for effective rainfall should be established for Mam Tor based on historical behaviour, and these could be used to investigate the combined influence of predicted temperature and precipitation changes on landslide reactivation return periods. However, a quantitative investigation of the effect of predicted temperature changes is outside the scope of the current study because there is a lack of detailed information on key parameters for the Mam Tor area that are required to calculate reliable evapotranspiration values, for example, using the Thornthwaite equation as outlined by Shaw (1994). Qualitatively, predicted higher summer temperatures will result in increased evapotranspiration and hence soil moisture deficit, and therefore additional precipitation in the winter months will be required to trigger instability. This is likely to increase return periods for instability, but without a detailed study it is not known whether the temperature changes will reverse the trend of predicted increased instability (i.e. decreased return periods) indicated by consideration of precipitation only.

Implications of findings

The analyses presented in this paper have indicated that greater seasonality (i.e. differences between summer and winter values) and increased winter variability of precipitation will have a negative affect on the stability of the Mam Tor landslide, and reduced annual rainfall a positive affect. It is also expected, although not proven, that increased temperatures will also have a positive effect. The distribution of these factors across the UK could be examined to give an indication of the likely effects of predicted climate change for specific sites. In general, based on the UKCIP 2002 climate change data, factors that promote an increase in stability are most likely to dominate in the south of the UK and will be less so in the north (see Figs. 6 and 7 for predicted trends in temperature and precipitation for the UK, respectively). The potential influence of climate change on slope instability is clearly related to the specific site geometry and ground conditions.

For Mam Tor, it is predicted that wetter winters could be offset by a drier antecedent period. Landslides with a shorter antecedent period, or those that exhibit a strong response to relatively short-term rainfall events, could be more vulnerable to the predicted increased variability of winter rainfall, and so could experience a shorter return period for slope movements. However, slope instability caused by longer periods of antecedent rainfall may occur less often in response to drier summers with increased evapotranspiration.

Further site- and region-specific studies are required. The findings of this study are only directly applicable to those landslides with similar geometry and sub-surface conditions and that experience both a current and future climate similar to Mam Tor.

Studies such as reported in this paper have raised concerns in the UK that climate change could result in reactivation of currently stable landslides, and/or increased activity of unstable slopes, and that this could lead to increased disruption to infrastructure such as transportation links, utilities and buildings. This has led to the formation of a UK network of stakeholders (i.e. the owners and managers of infrastructure), universities and government institutions to identify and prioritise future research on the impact of predicted climate change on slope instability. The CLIFFS (Climate Impact Forecasting For Slopes) Network is managed by the lead author and is funded by the UK Engineering and Physical Sciences Research Council. The Network is developing research proposals to extend preliminary studies (i.e. Mam Tor, among others) to all areas of the UK, so as to assess the full range of both current and predicted climates and geological formations. The aim is to assess the future stability of a range of slope failure types (i.e. shallow, deep seated and flow slides) across the UK. A key element of future studies will be the use of probabilistic data for predicted changes in precipitation and temperature, and consideration of uncertainty in the climate data.

Table 3 Measured mean monthly temperatures (°C) for the 1961–1990 period and predicted by Hulme et al. (2002) for the medium–high scenario in the 2080s

Period	January	February	March	April	May	June
1961–1990	2.3	1.9	3.8	6.0	9.2	12.5
Medium–high scenario 2080s	4.8	4.3	6.3	8.8	12.2	15.9
Period	July	August	September	October	November	December
1961–1990	14.3	13.8	11.6	8.7	4.8	3.1
Medium–high scenario 2080s	18.2	18.2	15.9	12.5	8.0	5.9

Conclusions

Climate changes predicted by UKCIP 2002 have been applied to a statistically based rainfall threshold model and used to investigate the future stability of the Mam Tor landslide in the UK. For predicted changes in precipitation, it is shown that return periods for the exceedence of the combined 1-month trigger and 6-month antecedent total rainfall thresholds established by Waltham and Dixon (2000) could fall from 4 to 3.5 years by the 2080s based on the UKCIP medium–high scenario. All four climate change scenarios give a reduction in return periods. There is also likely to be a shift from instances of instability in late Autumn to Winter. The model exhibits the most sensitivity to mean rainfall, especially in the winter months. A detailed assessment of the influence of predicted temperature increases was not possible due to a lack of historical data on key parameters that are required to validate any model used. However, it is likely that higher temperatures will tend to increase stability (i.e. increase return periods for movements) due to higher evapotranspiration and hence reduced effective rainfall.

Analyses have shown that greater seasonality and increased winter variability of precipitation will have a negative affect on stability, and reduced annual rainfall a positive affect. By examining climate change predictions for these factors at specific sites in the UK, in conjunction with an assessment of landslide vulnerability to extreme winter events, the likely impact of climate change could be assessed using the relatively simple approach outlined in this paper, validated using historical records of climate and slope movement. However, there is also the need for site- and region-specific information on relationships between climate, groundwater and slope instability to enable deterministic investigation of the likely impact of predicted climate change, and to allow validation of the simpler probabilistic approaches. Concerns in the UK have led to the formation of the CLIFFS Network to coordinate future research into the impact of predicted climate change on slope instability, and hence to assess possible impacts on the built environment.

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