Antecedent precipitation as a potential proxy for landslide incidence in South West UK

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Abstract

This paper considers the effects of antecedent precipitation on landslide incidence in the UK. During 2012-2013 an extraordinary amount of precipitation resulted in an increase in the number of landslides reported in the UK, highlighting the importance of hydrogeological triggering. Slope failures (landslides on engineered slopes) in particular caused widespread disruption to transport services and damage to property. SW England and S Wales were most affected. Easy-to-use and accessible indicators of potential landslide activity are required for planning, preparedness and response and therefore analyses have been carried out to determine whether antecedent effective precipitation can be used as a proxy for landslide incidence. It is shown that for all landslides long-term antecedent precipitation provides an important preparatory factor and that relatively small landslides, such as slope failures, occur within a short period of time following subsequent heavy precipitation. Deep-seated, rotational landslides have a longer response time as their pathway to instability follows a much more complex hydrogeological response. Statistical analyses of the BGS landslide database and of weather records has enabled determination of the probability of at least one landslide occurring based on antecedent precipitation signals for SW England and S Wales. This ongoing research is of part of a suite of analyses to provide tools to identify the likelihood of regional landslides occurrence in the UK.

Keywords Antecedent, rainfall, regional, national, landslide, slope failure, UK

Introduction

Large parts of the United Kingdom experienced several months of above-average precipitation from April to December 2012 making it one of the wettest periods of time for the country since meteorological records began. Throughout this period and into early 2013, a marked increase in the number of landslides was widely reported and captured in the National Landslide Database (NLD) of the British Geological Survey (BGS; Figs 1 and 2; Pennington and Harrison 2013). Tragically, four people were killed and at least six people were injured. The dominant type of reported landslide is slope failure, often a relatively small landslide occurring on engineered slopes and capable of disrupting transport services and causing damage to property, infrastructure and businesses. While these slope failures are, by far, the most frequent landslide type in the data, the impacts therefore tend to be minor and remediated within a few days. This is in contrast to less frequently reported, larger landslides on natural slopes that take many more resources and time to remediate.

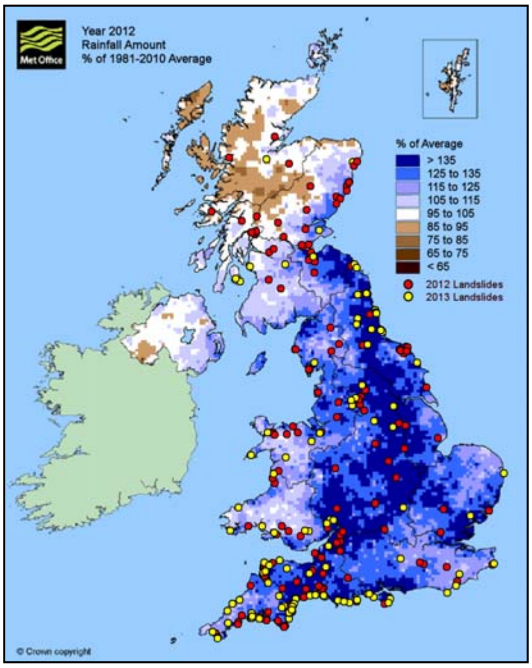

Fig. 1 Landslides reported in Great Britain in 2012 (red) and Jan-Jul 2013 (yellow) and the precipitation amount as a percentage of the long term average [source: MetOffice].

Landscapes evolve over time, continuously adjusting to achieve equilibrium conditions of stability and responding to influences in a highly complex system; active slope instability is a highly visible outcome of this process (Dijkstra and Dixon, 2010). Precipitation provides a spatially distributed trigger mechanism capable of driving these adjustments and the ability to quantify relevant thresholds is of great practical value in enhancing the planning, preparedness and response modes to these disrupting phenomena. Its potential use has been demonstrated around the world on the site- and catchment-specific scales through the long-term instrumentation and monitoring of slopes (e.g. Baum and Godt, 2009; Crozier, 1999; Minder *et al*., 2009; Prokešová *et al*., 2013; Rutter and Green, 2011). Regional thresholds defined for areas of similar meteorological, climatic, physiographic and soil characteristics are potentially suited for landslide warning systems based on quantitative spatial precipitation forecasts, estimates, or measurements (Guzzetti *et al*., 2008). These thresholds are dependent on a range of reliable data gathered systematically over a long period of time, e.g. reporting research on UK field study sites including the Mam Tor landslide, Derbyshire (Dixon & Brook, 2007; Rutter and Green, 2011) and BGS managed field sites of natural slopes at Hollin Hill and Aldbrough in Yorkshire (Gunn *et al*., 2013; Chambers et al. 2010) and engineered slopes such as the Victorian railway embankment at East Leake (Gunn *et al*., 2011).

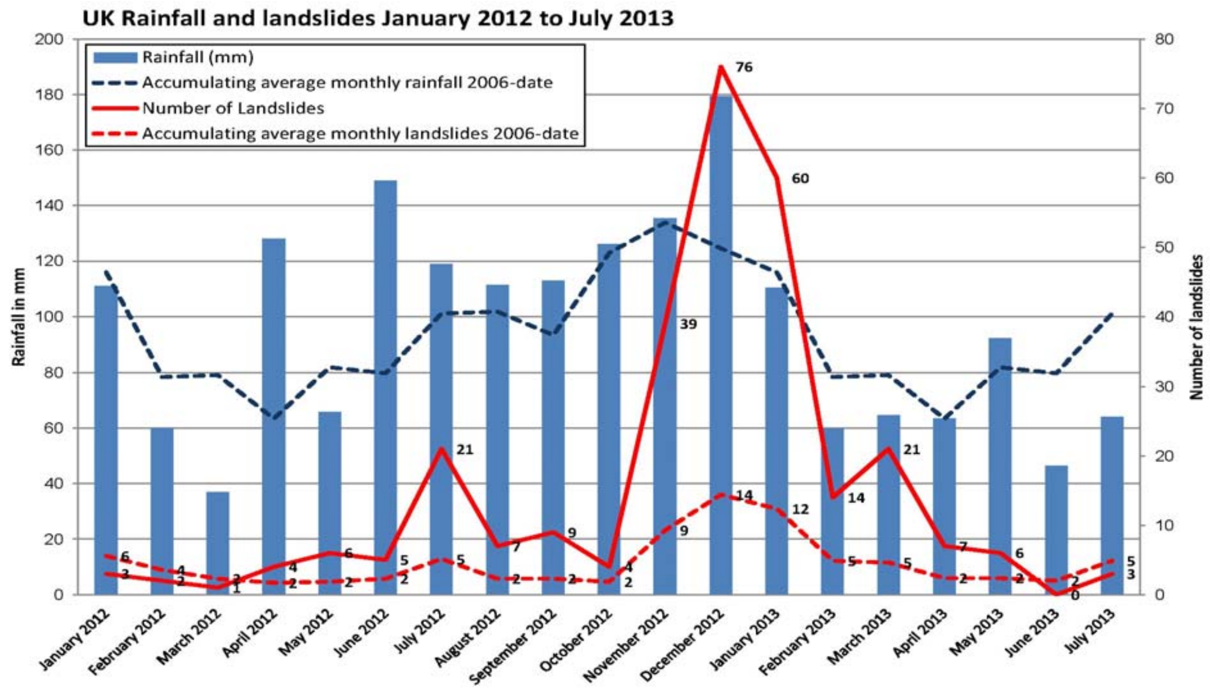

Fig. 2 Precipitation [source: MetOffice] and landslide incidence {source: BGS] in the UK from January 2012 to July 2013.

This paper discusses preliminary investigations into the empirical relationship between landslide occurrence and precipitation antecedence in the meteorological region of SW England and S Wales. The paper focuses on the period from January 2006 to July 2013 with special attention to the peak in reported landslide events during a very wet period from November 2012 to January 2013 (Fig. 2) and identifies antecedent precipitation as a potential proxy to communicate the likelihood of landslide incidence through, for example, the Natural Hazards Partnership (NHP) where the BGS issues a daily landslide hazard warning using a traffic-light^{plus} system (green, yellow, amber, red; British Geological Survey, 2013).

BGS National Landslide Database (UK)

The Landslides Team at the BGS catalogue landslide information in the NLD. It is used for a wide range of applications including their national landslide susceptibility map GeoSure (e.g. Booth *et al*., 2010; Foster *et al*., 2011; Pennington *et al*., 2009). The BGS NLD is the most comprehensive source of information on landslides in Great Britain and currently holds records of over 17,000 landslide events that are continually updated and added to as information is reported (Foster *et al*., 2012). Each of the landslide event records can hold information on over 35 attributes including location, dimensions, landslide type, trigger mechanism, damage caused, slope aspect, material, movement date, vegetation, hydrogeology, age, development and a full bibliographic reference. The information within the database is corporately maintained and held in a digital format that can be adapted and updated. For information on the history of the NLD see Foster *et al*. (2012).

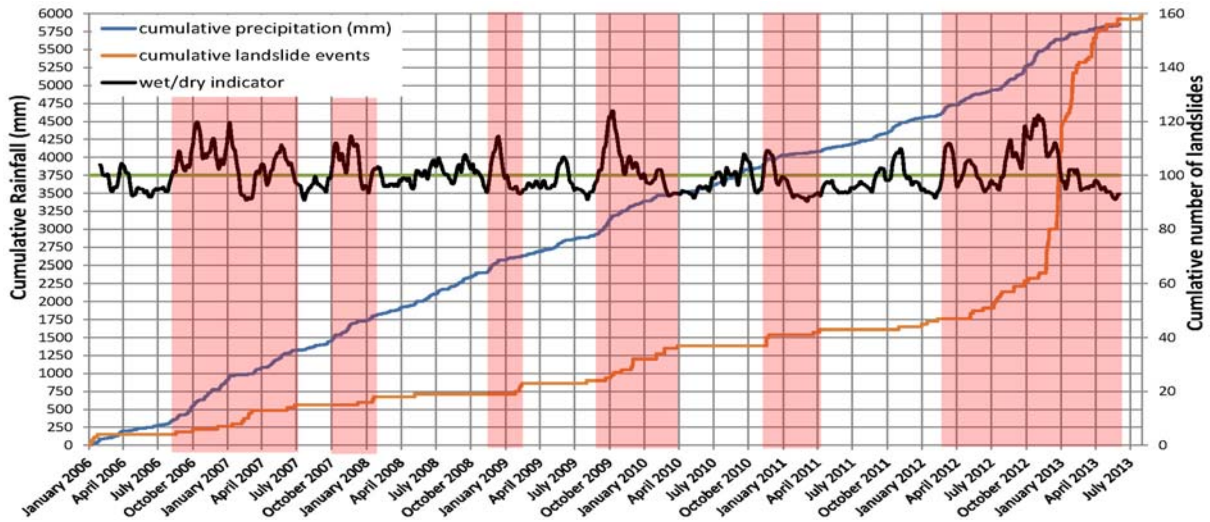

Fig. 3 Landslides and precipitation correlation (pink) in SW England/S Wales highlighted using a wet/dry indicator (proportional difference between actual and long-term average (LTA) precipitation where 100 represents equality and values > 100 show actual conditions wetter than LTA). (Landslides information from BGS NLD; weather data from MetOffice and Wunderground.com).

Information Sources

As well as routinely collecting data from ongoing regional geological surveys (e.g. Evans *et al*., 2013) and the published scientific literature, the online press has been monitored for information about landslides through various Internet search engines since 2006.

In August 2012, social media were incorporated into this search. Twitter, a popular micro-blogging tool where real-time observations are published to the web, has proved to be the most prolific source of information as it has for other geohazards such as earthquakes and tsunamis (e.g. Earle *et al*., 2011; Doan *et al*., 2012; Stollberg and de Groeve, 2012). This instantaneous reporting (‘tweeting’) mainly responds to events that have an immediate impact on society such as travel disruption and it has resulted in small slope failures being captured in the NLD. Previously, these small events would not be as visible in the regional and national media and would thus have a much lower likelihood of being recorded in the NLD.

Antecedent precipitation and landslide incidence

SW England and S Wales were most affected by excessive precipitation and reported landslides (Figs 1 and 3). SW England has a number of areas of concentrated landsliding, mainly associated with outcrops of Jurassic or Cretaceous formations such as the East Devon Upper Greensand upland slopes which have undergone large scale landsliding and the West Dorset Jurassic clays. The more stable slopes in the west underlain by Carboniferous and Devonian rocks are less likely to fail but there are a number of shallow planar failures in this region, mainly associated with changes in ground water and failure occurring within a drape of superficial materials. Particularly active areas of coastal landsliding can be found along the south coast from Lyme Bay to Poole Bay as well as the Devonian cliffs of north and south Devon. The valleys of the South Wales Coalfield have a long history of landslide activity mostly associated with the Carboniferous Coal Measures which has led to damage to residential and industrial property and the disruption of roads and services in a populous industrialised area (Conway *et al*., 1980).

To achieve an insight into the significance of antecedent precipitation for the triggering of landslides a number of analyses have been performed on the landslide dataset for SW England and S Wales. One set of analyses was performed using information from the very wet period from 01/11/2012 until 31/01/2013 when landslides were in the news frequently. Data captured over a longer period, March 2006 until August 2013, was used to evaluate long-term antecedent signals in the triggering of landslides. A large proportion of these landslides (43%) took place on man-made slopes such as road and railway embankments and cuttings. These slope failures are usually small-scale slumps or flows. Reported observations have shown that these are generally triggered by heavy precipitation and occur within a short period of time after prolonged heavy rain.

Winter 2012/13 Antecedent precipitation signal

The short period from November 2012 until January 2013 falls at the end of a very wet summer and autumn and a continuous period of above-average precipitation, which resulted in further incidents of unstable slopes (Fig. 2). Low temperatures and frequent precipitation justified the use of unadjusted 'total' precipitation to analyse landslide response to antecedent precipitation. For three types of landslides (falls, slope failures and translational slides) a series of correlation coefficients were determined relating landslide type to antecedent precipitation period (1, 2, 7, 30, 60, 90 and 120 days; Fig. 4). Slope failures correlate most closely with short duration antecedent precipitation (1, 2 and 7 days), followed by translational slides (7 and 30 days) and then falls (60 days). However, the outcomes are not very robust as the number of observations is low. The observations do enable investigation of the antecedent precipitation signal and this, in turn, can be used to inform the understanding of the types of triggering precipitation over longer time periods. The antecedent precipitation signature required to trigger landslides was analysed against the number of observations per day (Fig. 5). The majority of events involved single events per day, but there were several days where a larger number of landslides were reported.

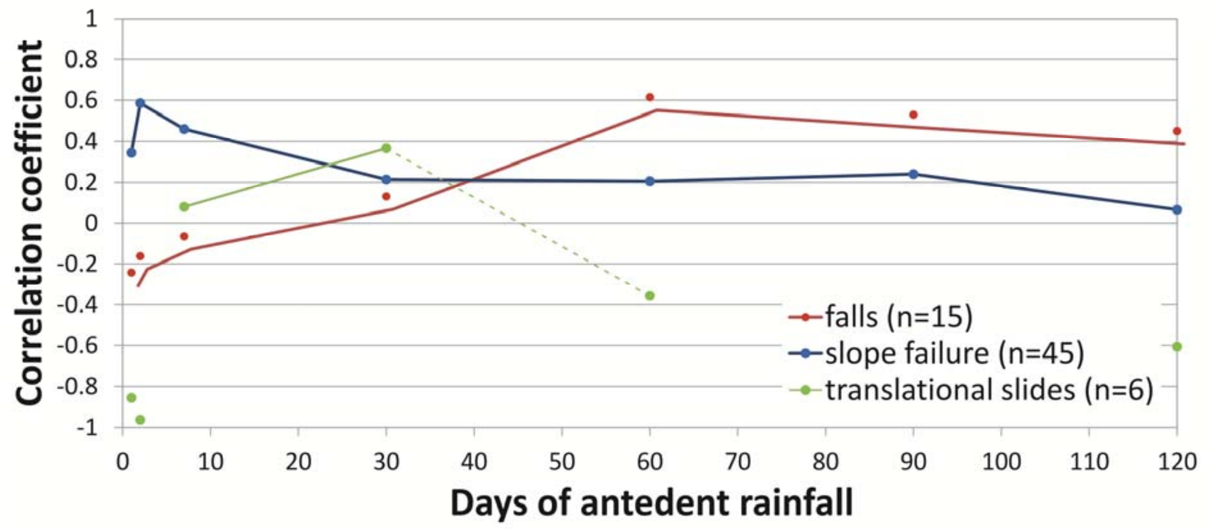

Fig. 4 Correlation coefficients for antecedent precipitation and landslide type for events between 01/11/12 and 03/01/13 in SW England and S Wales.

In Fig. 5 lines are drawn linking the lowest recorded antecedent precipitation signals. It appears that when 6 or more landslides are recorded per day in the study region, a steady signal becomes more apparent as a spatially distributed trigger mechanism is required to drive these larger numbers of failures. Clearly, when fewer landslides occur per day the spatial relevance of the triggering mechanism diminishes and specific local conditions start to overshadow the antecedent precipitation signal. To inform the threshold model of how much precipitation is required to result in widespread unstable slopes, the antecedent precipitation sequence of the 9 landslides per day event has been selected (Fig. 6). The antecedent signal clearly follows two trends – a steep section of conditions up to 7-days and a long-term, less intense accumulation from 7 to 90-days. This may suggest that a long period of precipitation is required to prepare the landscape for instability and that a final period of more intense precipitation is necessary to trigger landslides as has been clearly articulated by others in the UK context (e.g. Dixon and Brook, 2007; Collison *et al,*. 2000; Dijkstra and Dixon, 2010).

It appears that the trends of Figure 6 fit very well with the long-term average antecedent conditions. Further investigation of multiple events triggered per day during the same period of the year show that all fall on, or slightly above this trend. The trends could therefore be interpreted as a threshold envelope where antecedent precipitation plotted above the envelope is a signature for conditions 'wetter than usual' that can lead to multiple landslide events, and that signatures plotting below this trend represent conditions 'drier than normal', which would not result in precipitation-triggered landslides.

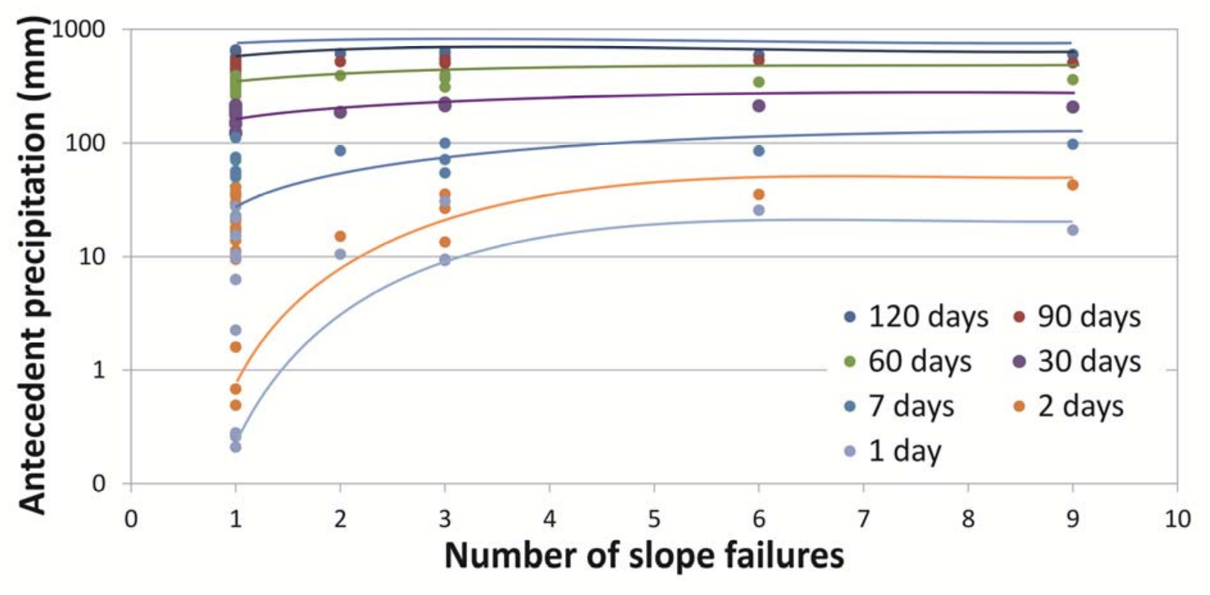

Fig. 5. Antecedent precipitation and number of slope failures per day. At 6 and 9 events per day the antecedent precipitation signal appears more consistent.

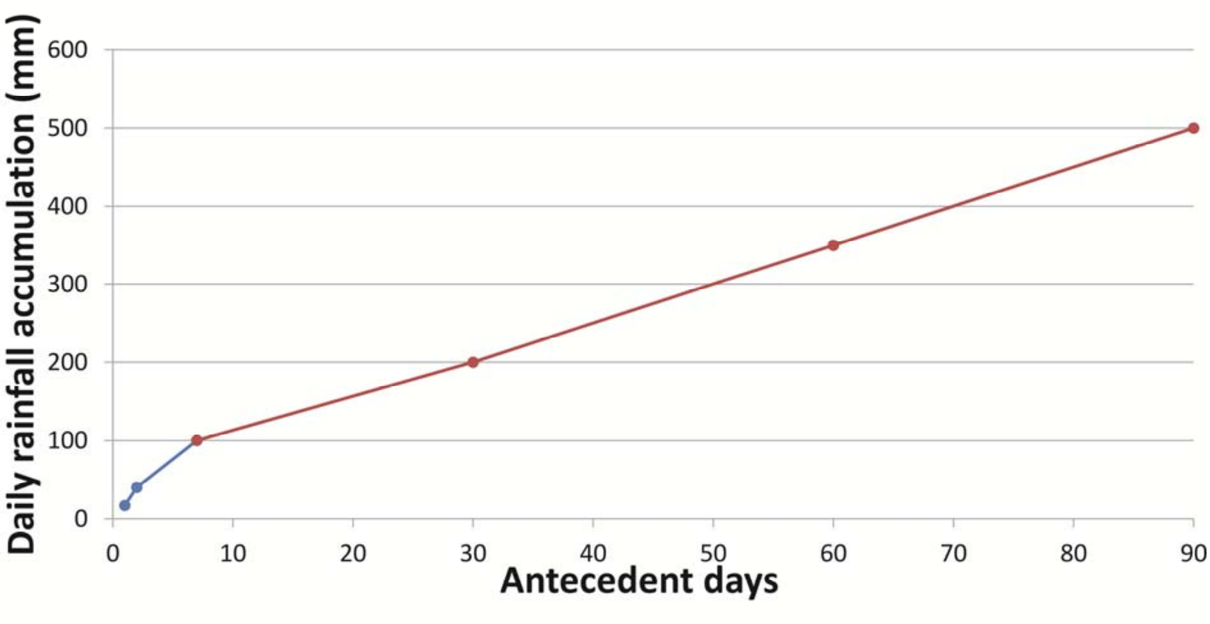

Fig. 6. Antecedent precipitation 'winter' threshold envelope for slope failure for SW England and S Wales. Event sequences plotting above the lines represent 'wetter than usual' conditions that can lead to multiple landslides.

To extend these observations to a longer time period (years, rather than months), it is necessary to estimate the proportion of total precipitation that can reach the ground surface once account has been taken of seasonal variations in evapotranspiration. This variation is quite considerable, and in summer months it will be rare if conditions persist that result in widespread slope instability. As discussed by Pennington and Harrison (2013) these conditions existed in 2012 leading to a record year for landsliding in Britain.

Probability of landslide occurrence

For the determination of a probability of landslide occurrence the database from 01/01/2006 until 31/07/2013 (2710 records) was used. For each date, information was available on numbers of landslides and seasonally adjusted antecedent effective precipitation for 1, 2, 7, 30, 60 and 90 days. A generalised linear model was fitted the data for the prediction of landslide events from antecedent precipitation over 1, 2, 7, 30, 60 or 90 days. The model was fitted using the generalised linear model (GLM) procedure in the MASS package for the R platform (Venables and Ripley 2002). A Poisson link function was used after exploratory analysis of a quasiPossion model. A subset of predictors was then selected using the stepAIC procedure in the MASS package, which uses stepwise backward predictor selection according to the Akaike Information Criterion. By this procedure the selected predictors for all landslides were antecedent precipitation over 1, 7 and 90 days. For slope failures/planar slides the selected predictors were antecedent precipitation over 1, 2, 7, 30 and 90 days. It must be noted that the records are affected by a perceived lower landslide capture success rate, particularly in the period before April 2012 (Pennington and Harrison 2013) and that this database contains zeros that do not always reliably indicate a non-occurrence of landslides, but rather that landslides were not recorded or reported. This is a reason for caution about interpretation of the fitted models. Nonetheless, these do provide evidence that long-term antecedent precipitation is an important factor in determining landslides occurrence. The fitted values of the GLM are the expected number of landslides according to the model on any data. Treating this as the parameter of a Poisson variable, one may compute the probability of at least one landslide occurring for (a) the full landslides dataset and (b) slope failures and planar slides. These probabilities are plotted along with the observed number of landslides on each day (Fig. 7a) and a subset including only slope failures and planar slides (Fig. 7b).

It is evident from these analyses that single landslide occurrence per date does not correspond well with the probability distribution. When several landslides occur per date there is a much better correspondence. The probability distribution for slope failures and planar slides results in a lower temporal dispersion when compared to the undifferentiated landslides probability distribution, suggesting a possible way forward for fine-tuning an antecedent precipitation signal dependent upon landslide type. Further analyses on longer periods are currently being investigated. Some landslide events appear not to be represented by elevated probability of occurrence (e.g. 12/2010) – this may be caused by local triggering precipitation not represented by the regional record used. Once a general model is better established, routes towards local differentiation and greater spatial relevance will be evaluated.

For a regional model intending to provide indicators of changes in the susceptibility of a landscape to generate landslides, this approach appears adequate. It provides a mechanism that can be tested against the 'expert-based' landslide hazard assessments that are carried out on a daily basis for the NHP. In the current situation, antecedent conditions are included in the reasoning to determine a regionally specific landslide hazard warning (following the traffic-light^{plus} communication, discussed above). The statistical model will now run alongside this assessment to test its performance and evaluate its potential as an objective method of determining landslide hazard warning status. This approach is part of a suite of tools in development at the BGS that includes developing the use of models that analyse temporal fluctuations in soil moisture and groundwater levels in the landscape veneer on a more detailed, slope specific scale.

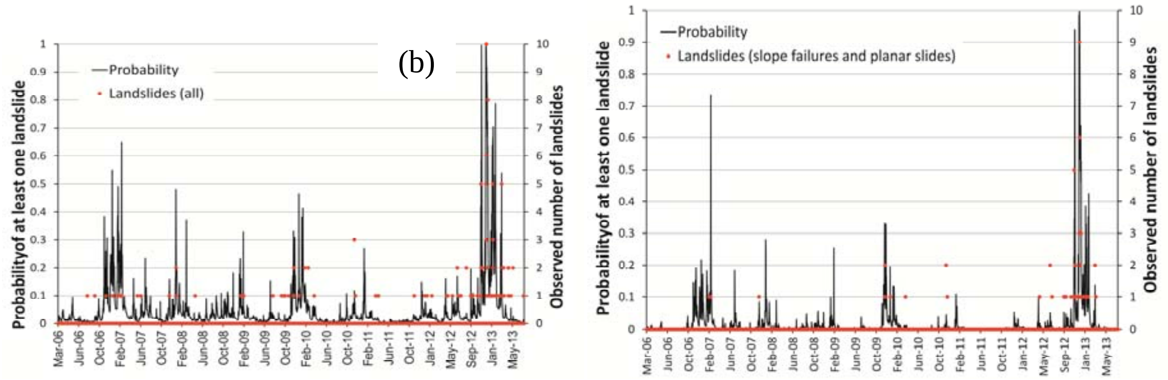

Fig. 7. The probability of at least one occurrence of any type of landslide (a) and slope failures/planar slides (b) on a given date taking into account antecedent precipitation conditions.

Conclusions

The weather information is based on generalised regional precipitation data. Finer spatial resolutions will enable determination of antecedent precipitation patterns of greater relevance to individual landslide occurrences. Conversion factors for the determination of effective precipitation provide an initial approximation of the amount of water reaching the top of the soil column. Further work is progressing using water balance models to determine how much water is available to affect effective stress changes at critical depths. Without exception, all the landslides reported in 2012-13 have been described in the media and social media because they have had an impact on society such as road diversions, rail delays, homes being demolished or the closure of coastal footpaths. While these are valid reports, the following scenarios must be considered to fully appraise the rise in landslides over the winter of 2012/2013 period:

- The data represent an accurate picture of the true number of landslides occurring;
- The data are artificially high due to a heightened awareness of landslides through added media attention following four fatalities in SW England by three separate landslide events in 2012-13;
- The data give a false impression of more landslides occurring when there were just fewer reported prior to August 2012 due to the timing of the inclusion of social media information sources also coincident with the rise in precipitation and landslide reports;
- The data under-report the true number of landslides occurring as the social impacts were insufficient to warrant reporting. This may be especially true for those larger and older landslides which may have started to reactivate but have no immediate impact for the public.

Once the reliability of these models has been evaluated they provide an opportunity to forecast changes in landscape instability based on weather forecasts and an analysis of the results in the context of long-term forecasted changes in weather event sequences, such as those derived from UKCP09.

Acknowledgments

The authors would like to thank BGS staff: H Reeves, V Banks, H Jordan, D Boon, P Hobbs, M Kirkham & G Jenkins; the Met Office. The authors publish with the permission of the Executive Director of the BGS (NERC).

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