Combining landslide susceptibility maps and rainfall thresholds using a matrix approach

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ABSTRACT

On the regional scale, investigations on future landslide can broadly be distinguished in spatial or temporal analyses, i.e. landslide susceptibility or hazard maps, and landslide triggering rainfall thresholds. Even though both approaches have its uses e.g. in spatial planning, risk management and early warning, they also have limitations. Susceptibility and hazard maps do not contain information on when landslides will be triggered, while rainfall thresholds give no detailed indication on where a landslide might take place. The combination of spatial and temporal landslide research remains a complex issue and no ready-to-use methodology for combined spatio-temporal landslide analyses is presently available. In our study, we present a simple matrix approach to combine spatial and temporal landslide probabilities and highlight its application for a case study in the Wudu region, China. Landslide susceptibility mapping is based on a previous study involving logistic regression; the analysis of rainfall threshold was carried out applying the daily rainfall model. A 4x4 matrix was used to combine and reclassify the spatial and temporal landslide information. The results are then plotted on a map to highlight the susceptibility for rainfall events with varying likelihood of triggering landslides.

KEYWORDS

Landslides; susceptibility mapping; rainfall thresholds; matrix approach; China

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1. Introduction

Landslides are an important geomorphological hazard and are responsible for significant damage to infrastructure as well as loss of lives. Petley (2012) reported an annual death toll of approximately 1600 due to non-seismic landslide events alone, the majority of these occurring in Asia. Yin *et al.* (2009) estimated an average of 700 to 900 landslide related fatalities per year for China. In particular large seismic shocks can result in substantial landslide activity. For the 2008 Wenchuan earthquake (magnitude M7.8), more than 20,000 landslide were reported and attributed to a third of the approximately 60,000 fatalities (Huang and Li, 2009). Consequently, the prediction of future landslides in space and time is crucial and should be fostered.

Landslide investigations generally concentrate on either the local scale, i.e. single slopes, or the regional scale, i.e. larger regions (Thiebes, 2012). While the former scale is a focus of engineering geology and related disciplines, the latter scale has intensively been worked on by geomorphologists and geographers. The basis of most regional scale landslide studies are landslide inventories, i.e. maps showing the location of landslides within the region. These can be used to compute landslide susceptibility maps depicting the spatial probability of slope failures using a wide range of approaches utilising Geographic Information Systems (GIS). The methodologies to estimate landslide susceptibility can broadly be divided into heuristic, statistic and deterministic approaches (Soeters and Van Westen, 1996; Van Westen *et al.*, 2006). Ordinary logistic regression is one of the methods that has been used extensively to map landslide susceptibility (e.g. Atkinson and Massari, 1998; Süzen and Doyuran, 2004; Akgün and Bulut, 2007; Greco *et al.*, 2007; Bai *et al.*, 2009, 2010b, 2012). Matrix approaches have also been used to produce regional scale landslide susceptibility maps (DeGraff and Romesburg, 1980; Fernández *et al.*, 1999, 2003; Irigaray *et al.*, 2007; De Graff *et al.*, 2012). A main shortcoming of susceptibility maps is the lack of information on the

temporal probability of landslides as well as on the magnitude of potential slope failures.

The regional scale analysis of the temporal probability of landslides strongly relies on the assessment of landslide triggering rainfall thresholds. This field of research has essentially been established by the works of Caine (1980) who put forward the first relationship between the intensity and duration of rainfall events and the triggering of landslides. Since then, many other researchers have established critical rainfall characteristics by the same methodology (Jakob *et al.*, 2006; Matsushi and Matsukura, 2007; Crosta and Frattini, 2008; Guzzetti *et al.*, 2008; Capparelli *et al.*, 2009; Cepeda *et al.*, 2010; Saito *et al.*, 2010). Other empirical thresholds have been determined based on antecedent rainfall (Sorriso-Valvo *et al.*, 1994), daily rainfall (Crozier, 1999; Glade, 2000) and event rainfall (Bell and Maud, 2000), cumulative event rainfall (Canuti *et al.*, 1985; Corominas and Moya, 1999), cumulative event rainfall and event duration (Innes, 1983; Wilson *et al.*, 1992; Zêzere and Rodriguez, 2002), and thresholds based on mean annual precipitation and normalised rainfall (Giannecchini, 2005; Sengupta *et al.*, 2009). Over the past years, a wide range of critical rainfall thresholds have been developed and an extensive overview is available on the website of the Italian Research Institution IRPI (rainfallthresholds.irpi.cnr.it). It should also be noted that regional scale landslide early warning systems, e.g. in Hong Kong (Yu *et al.*, 2004), Seattle (Chleborad *et al.*, 2008) and Italy (Rossi *et al.*, 2012), rely on rainfall thresholds for alerting civil protection and the general public.

At present, there is no general consensus on how landslide susceptibility maps and landslide triggering rainfall thresholds should be combined. However, a map combining both spatial and temporal landslide probabilities could aid spatial planning, civil protection agencies and the general public to deal with landslide hazards. In this paper, we present a straightforward matrix approach to combine a landslide susceptibility map and landslide triggering rainfall thresholds. To highlight our approach, we utilise a landslide susceptibility

map created using logistic regression (Bai *et al.*, 2013a) and rainfall thresholds established using the daily rainfall model (Bai *et al.*, 2013b). Our approach combines spatial and temporal landslide occurrence probabilities using a simple 4x4 matrix to create a combined map; however, the method could easily be modified to accommodate different numbers of combination classes. The study area of our investigations is the Wudu region in China's Gansu province, an area that is substantially affected by landslide and frequently suffers landslide losses.

2. Matrix approaches in landslide hazard and risk studies

Matrix approaches have been used for landslide susceptibility, hazard and risk studies in various research applications. Frequently, matrixes have been utilised to combine different aspects of landslide hazards with the aim to derive a new index value which can be used for further analysis or to aid decision-making on landslide risk management. Moreover, matrix approaches have been highlighted as a helpful tool to harmonise existing landslide hazard information available in different countries and territories. One such example was provided by the AdaptAlp project (2011) which aimed for a comparison, evaluation, harmonisation and the improvement of different methods of hazard mapping. Here, a matrix approach was proposed to combine spatial and temporal probabilities of landslide processes to receive a unified qualitative probability.

Matrix approaches have often been employed to determine a basic risk index by combining hazards and consequences. A hazard-consequence matrix approach was proposed by Chowdhury and Flentje (2003) to provide a qualitative estimation of landslide risks. The authors note that the hazard may thus be evaluated separately from the consequence based on site inspections. Moreover, consequences may be assessed separately for loss of life and economic losses. Kjekstad (2007) proposed a similar matrix approach to carry out preliminary landslide risk assessment in particular for developing countries. Therein, three hazard classes from low to high are combined with three

consequence classes. Consequence classes are based on a complex scoring system which takes into account e.g. the number of dwellings, the existence of critical infrastructure and life lines. The resulting risk index values range from one to five and aim to assist the prioritisation of high risk areas. Similar qualitative risk evaluations based on the combination of the likelihood of landslides and the potential consequences have been widely used by scientists (Ko Ko *et al.*, 2004a, 2004b) and practitioners and have been included in respective guidelines (Kohler *et al.*, 2004; Tonkin & Taylor Ltd, 2006).

Another field of applications for matrixes in landslide studies focuses on describing the hazard by combining the intensity of the processes with the occurrence probabilities. The most prominent matrix approach based on this concept was put forward by the Swiss Federal Office for the Environment (BUWAL) and combines the intensity and occurrence probability or recurrence intervals of hazard processes including rockfalls, landslides, and avalanches (Latelin, 1997; Bundesamt für Umwelt Wald und Landschaft, 1998). In the BUWAL framework for hazard assessments, class boundaries of intensities and occurrence probabilities are determined by quantitative values such as kinetic energy (rockfalls), pressure (avalanches), thickness of mobilised material (debris flows) and movement speed (landslides). However, to make the methodology more approachable by practitioners and to ease its use for the prioritisation of counter measures, intensity and recurrence intervals are rather included as qualitative classes (i.e. low, medium, high). The resulting hazard index values are then plotted on a map to aid spatial planning by restricting building activities to areas with low or medium hazard values (Raetzo H. *et al.*, 2002); for the latter certain building codes have to be respected. The BUWAL approach has also been used by other researchers, as well as regional administration dealing with landslides and other natural hazards (SafeLand Project, 2010; Paramount Project, 2012).

Additionally, matrixes have been employed to combine landslide susceptibility maps with information on the likelihood of their occurrence.

One such example was provided by researchers in France (Thiery *et al.*, 2006; Thiery, 2007). After estimating regional landslide susceptibility using a statistical bivariate weight of evidence approach, the occurrence probability was assessed using a deterministic landslide model calculating safety factors. The results were then combined to receive a new hazard index value which aimed to better describe the landslide hazard conditions in the region than the two input model results alone. In another study, Bell *et al.* (2014) used two different 4x4 matrix approach to combine landslide susceptibility classes with hydro-meteorological index values to receive warning classes to be included in the national scale early warning system for shallow landslides and debris flows in Norway. Their results showed that the combined warning classes improved warning procedures significantly.

Recently, matrix approaches have also been utilised in landslide studies using satellite-based InSAR (Interferometric Synthetic Aperture Radar), in particular for the updating of existing landslide inventories and hazard maps. Cigna *et al.* (2012) acquired information on the state of activity as well as on the intensity of landslide movements for a pre-existing inventory of slope movements based on the PSI approach (Permanent Scatterer Interferometry). The results are then combined in a matrix to yield updated information on the state of landslide activity (i.e. active, reactivated, stabilised, dormant). For newly detected slope movements, i.e. landslide not contained in the existing landslide inventories, the state of activity is derived based on a matrix combining historic PSI analyses results with more recent data. Another example of a matrix approach in landslide-focused InSAR research was presented by Lu *et al.* (2014). Here, an existing landslide inventory that included information on the intensity of the processes derived from geometrical properties of the slope movements was combined with InSAR-based measurements of the displacement. The resulting new intensity classes are then integrated in a risk assessment and an estimation of potential economic losses.

3. Study area

China is one of the countries with the world's most serious geological disasters and experiences high economic losses every year. For the period from 2006 to 2008, a total number of 154,748 geological disasters were recorded by the China Institute of Geo-Environment Monitoring of which 118,351 were landslide-related, thus accounting for approximately 76% (China Geological Survey Bureau of Statistics, 2008). The annual direct economic damage of landslides has been estimated to be approximately 10 billion RMB (approximately US-\$ 1.3 billion) in addition to 700 to 900 fatalities per year (Yin, 2009). These numbers strikingly underline the importance of spatial and temporal landslide predictions, hazard and risk analyses, and disaster prevention measures.

The study area of this research is the Wudu region in western China (Fig. 1). It covers an area of 4,683 km² and belongs to the prefecture-level city of Longnan in Gansu province. The Wudu region in Gansu province is a hot-spot of landslide activity (Scheidegger and Ai, 1987; Bai *et al.*, 2010a, 2012) and was severely affected by the 2008 Wenchuan earthquake which caused hundreds slope failures (Cui *et al.*, 2009; Chigira *et al.*, 2010; Bai *et al.*, 2013a). In addition, the earthquake deteriorated the area and made it more susceptible for future landslides (Jiao and Wang, 2010). Such secondary hazards are a major concern for local and regional decision-makers who require reliable information on current and future hazard conditions. The geological structure is dominated by the southern Qinling fold system. During the geologically recent Yenshan and Himalayan crustal movements, uplift and complex faulting of the region took place, resulting in widespread valley incision and undercutting of the slopes (Derbyshire *et al.*, 1999). Current uplift rates in the study area are high and enhance geomorphological activity (Chen *et al.*, 2006). The lithology of the study area consists of soft and erodible formations which are primarily marine metamorphic and carbonate rocks. Elevations in the study area range from 600 m to over 3500 m a.m.s.l.

Figure 1 Location of the Wudu region (grey area) in southern Gansu province, China

The steep slopes of this rural region are often terraced and are used for agriculture. The Wudu region belongs to the drainage system of Bailongjiang river which is a tributary of the Yangtze (Changjiang) river. The area is influenced by warm and humid subtropical monsoon climate and experiences orographical effects due to the mountainous topography. Thus, climatic conditions vary strongly with elevation and topographical position. Regional governmental agencies use simple, empirical rule of thumb (Chen *et al.*, 2006) to roughly estimate the annual precipitation for different elevations; altitudes below 1500 m receive approximately 400 mm per year, while elevation between 1500 and 2000 m receive an annual rainfall of 500 to 600 mm, and elevation above 2000 m experience more than 600 mm of rainfall each year. The annual rainfall distribution shows a significant peak during summer (May to September), when approximately 80% of the annual rainfall is recorded. Rainfall events usually have durations of several days, but also short events with high intensity (up to 40 mm per hour) occur.

The combination of high relative relief, steep slopes and weak lithology, as well as the triggering influence of strong monsoonal rainfall and frequent earthquakes result in both large localised slope failures and widespread landslide occurrences. The Wudu region has long been known to be extremely prone to landslides and been rated as one of China's most severely landslide-affected regions (Scheidegger and Ai, 1987). According to the landslide classification by Cruden and Varnes (1996), the landslides in the Wudu region are mostly translational and rotational slides of loess and colluvial material which in some cases have a flow type run-out. Earthquakes and human activities (e.g. slope cutting and irrigation) have frequently triggered landslides but in particular rainstorm events have been reported to be of major importance for landslide triggering, with 95% of the landslides occurring in the rainy season from May to September and the more than half of all landslides occurring in August and September (Chen *et al.*, 2006). In addition, 60% of all recorded slope failures took place in years of annual rainfall above average.

Widespread landslide activity was particularly observed in the 1980s. In 1982, eight times more landslides than on average occurred as a consequence of heavy rainstorms in that year. Another significant event took place on August 3, 1984, when heavy rainfall caused more than 400 debris flows and 570 landslides which together affected approximately 9.3 million people and caused a direct economic loss of 265.26 million Yuan (approximately 30 million Euro) (Chen *et al.*,

2006). Over the last four decades at least 567 people were killed by landslides in the Wudu region (China Geological Survey Bureau of Statistics, 2008). One of the most recent destructive landslide events that was also reported in international news took place on August 8, 2010, in Zhouqu County, where a fast moving debris flow swept through the city destroying large areas and claimed at least 1287 lives (Yu *et al.*, 2010).

Figure 2 Distribution of rainfall-triggered landslides in the period from 1995 to 2003 in the Wudu region

4. Generation of input data

4.1 Historical rainfall-triggered landslide inventory

The 'Ministry of Land and Resources of the People's Republic of China' has been working on geo-hazard survey plans in counties seriously affected by geo-hazards since 1999. The 'Longnan First Station for

Landslide and Debris Flow Forecasting and Warning System of the Upper Reaches of the Yangtze River' was constructed in 1991. Both institutes provided information on landslide occurrences which were used to derive an inventory of rainfall-induced landslides between 1995 and 2003 for the Wudu region. The recorded attributes include spatial characteristics (location, length, width, volume), temporal information (day of failure), damage

information (people affected, damage caused) and additional information (e.g. landslide type and triggering conditions). For the period between 1995 and 2002, a total number of 217 rainfall-triggered landslides were recorded. In 2003 alone, 290 landslides and 360 debris flows triggered by seven rainfall events are listed. In total, 507 landslides are contained in the inventory (Fig. 2).

4.2 Landslide causative factors

Topographical information in the form of a digital elevation model (DTM) with a pixel size of 30×30 m

was created by digitising a 1:50,000 topographical map. Subsequently, all other spatial input data was set to the same pixel size independent of the scale of the original data source. The DTM was also used to derive topographical characteristics such as elevation, slope angle and aspect using ArcGIS tools. Rivers and roads were digitised manually from the topographical map. Information on lithology was available in the form of the geological map (1:200,000) which was reclassified (Chen *et al.*, 2006) to cluster eight lithological units which have similar physical-mechanical characteristics (Fig. 3).

Figure 3 Lithological units and faults in the Wudu region (based on the 1:200,000 geology map) (modified after Bai *et al.* 2013b)

Land use types were mapped using pre-processed Landsat MSS, TM and ETM images (Liu *et al.*, 2003; Wu *et al.*, 2004). After geometrical correction and georeferencing of the images, the average location errors were found to be less than 50 m (about 2 pixels). The accuracy of the landuse interpretation was validated in the field by random checks and resulted in an accuracy of the land-use classification of 92.9% (Liu *et al.*, 2003). An annual average rainfall (1971-2009) map based on the data from 16 stations of which 9 are located within the study area were available to this study. The data from the respective stations were used for a spatial interpolation of annual precipitation using the kriging function (linear variogram model) in ArcGIS. Orographic effects of topography on rainfall distributions were not taken into account. In addition, daily rainfall measurements from five weather stations for the period from 1995 to 2003 were available and used to estimate the antecedent rainfall conditions of landslides in the study area.

5. Spatial-temporal landslide analyses

5.1 Spatial landslide analysis

In this study, the results of a logistic regression analysis of spatial landslide susceptibility were used (Bai *et al.*, 2013a). The algorithm of logistic regression applies a maximum likelihood estimation after a transformation of the dependent variable into a logic variable, which is representing the natural log of the odds of the dependent variable occurring or not. In this way, the logistic regression estimates the probability of a certain event occurring (Atkinson and Massari, 1998). In this study, the dependent variable is a binary variable representing the presence or absence of landslides. The logistic model can be expressed in its simplest form as:

$$P = \frac{1}{1 + e^{-z}} \quad (1)$$

where, P is the probability of an event (landslide) occurrence, which varies from 0 to 1 on an s-shaped curve; z is defined as the following equation (linear logistic model), and its value varies from $-\infty$ to $+\infty$:

$$z = \hat{\beta}_0 + \hat{\beta}_1 x_1 + \hat{\beta}_2 x_2 + \dots + \hat{\beta}_n x_n \quad (2)$$

Where $\hat{\beta}_0$ is the intercept of the model, n is the

number of independent variables, $\hat{\beta}_i$ ($i = 1, 2, 3, \dots, n$) is the slope coefficient of the model, and x_i ($i = 1, 2, 3, \dots, n$) is the independent variable. The linear model formed shows the relation of the dependent variable (presence of a landslide (1) or the absence (0) of a landslide) and the independent variables (pre-failure conditions) (Bai *et al.*, 2010b).

The landslide susceptibility mapping by the logistic regression model includes five main steps: (1) sampling of the data set; (2) splitting of the dataset by random selection into a calibration and validation sub-set; (3) multi-collinearity diagnosis by an analysis of the tolerance (TOL) and variance inflation factor (VIF); (4) application of logistic regression model; and (5) validation and evaluation of the model results by calculating the receiver-operating characteristics (AUROC).

For the landslide susceptibility analysis all 507 rainfall-triggered landslides were used. In total, 507 landslide and 507 non-landslide points were randomly selected. Input variables included topographical factors (elevation, slope angle, aspect), lithological classes, land use classes and spatially interpolated annual average precipitation (1971-2009). Categorized parameters such as lithology and land use were first transformed into a numerical variable (dummy variable) before they were included into the logistic regression model.

5.2 Temporal landslide analysis

In this study, the results of a landslide triggering rainfall threshold analysis were used (Bai *et al.*, 2013b). Critical rainfall conditions were determined by applying the antecedent daily rainfall model in combination with logistic regression to estimate landslide occurrence probabilities. This model is based on the research of Crozier and Eyles (1980), Crozier (1999), and Glade *et al.* (2000) and represents a conceptual approach to rainfall thresholds which are estimated based on soil

moisture conditions. A soil water status index is calculated based on the daily rainfall, and a decay factor which accounts for the loss of water due to evaporation and drainage from the soil over a period of days prior to a landslide event. The antecedent daily rainfall model was applied to the landslides triggered by the 2003 rainfall events in the Wudu region. From the available five meteorological stations, the highest daily precipitation records were assumed to be the triggering rainfall for the respective landslides. Due to missing local soil information, the decay constant k (representing the outflow of the regolith) was set to 0.84 and the r_n (maximum regional precipitation on the n^{th} day before 0) to 10 days. This value was chosen after initial analysis of rainfall data and is the same as in other studies (Crozier and Eyles, 1980; Aleotti, 2004). For the calculation of probability thresholds, days with landslide occurrences were treated as a binary variable. By a logistic regression, the correlation between the dependent variable (landslide occurrence) and the independent variables (antecedent daily rainfall r_a and daily rainfall at the day of slope failure r_d) was determined.

5.3 Combined spatio-temporal landslide analysis

In order to facilitate spatio-temporal landslide analyses, we adopted a simple matrix to combine the calculated spatial and temporal landslide probabilities. Thereto, the susceptibility map was classified into four equal interval classes, i.e. level 1 (very low susceptibility), level 2 (low susceptibility), level 3 (medium susceptibility) and level 4 (high susceptibility). Break points for the classes were chosen to be 0.25, 0.5 and 0.75. Similarly, the daily occurrence probabilities derived from both daily precipitation and antecedent rainfall were divided into four classes based on the daily landslide probability, i.e. level 1 (very low probability; <0.08), level 2 (low probability; $0.08-0.17$), level 3 (medium probability; $0.17-0.58$) and level 4 (high probability; >0.58). The combination matrix assigns a high index class to a high landslide susceptibility level and a high level of failure probability. In contrast, a low landslide susceptibility level and low landslide

occurrence probability level result in a low combined spatio-temporal index value. A very high spatial landslide probability combined with a low temporal probability results in the combined spatio-temporal class 2, and vice versa (Table 1). The combination of landslide susceptibility and occurrence probability was carried out with landslides that were not included in the previous determination of landslide occurrence probabilities and the respective rainfall thresholds. In total, 122 randomly selected landslides that have occurred prior to 2003 were used.

Table 1 Matrix used for combining landslide occurrence probability and susceptibility classes

Temporal probability	Spatial probability			
	Level 1	Level 2	Level 3	Level 4
Level 1	Class 1	Class 1	Class 1	Class 2
Level 2	Class 1	Class 2	Class 2	Class 3
Level 3	Class 1	Class 2	Class 3	Class 4
Level 4	Class 2	Class 3	Class 4	Class 4

6. Results

6.1 Susceptibility mapping

The application of the logistic regression model to estimate spatial landslide susceptibility resulted in a map (Fig. 4). High susceptibility classes can be found in the north-western part of the study area where the highest elevations and steepest slopes are present. The statistical analysis (Bai *et al.*, 2013a) of the influence of each variable showed that besides topographical aspects (primarily slope angle) lithological conditions control the spatial distribution of landslides. Herein, mudstone, siltstone and conglomerates are the most susceptible lithological units. In total, 46% of the rainfall triggered landslides are located in the highest susceptibility class, while 39% are within the class of medium landslide susceptibility. Analysis of the VIF and TOL showed values of less than 2 and more 0.4, respectively. The validation of the susceptibility map was carried out by analysing the prediction rate curves (Van Den Eeckhaut *et al.*,

2009). Results show prediction rates of 70.2% and 76% for landslides and non-landslides susceptibility class. The AUC (area under curve) value that

represents a quantitative measure of the model performance reached 0.782, thereby indicating a good model performance (Swets, 1988).

Figure 4 Landslide susceptibility map (modified after Bai *et al.* 2013a)

6.2 Landslide occurrence probability

The probability of failure as a consequence of daily and 10-day antecedent rainfall can be expressed by the following equation:

$$\log\left(\frac{p}{1-p}\right) = -5.26 + 0.22r_0 + 0.31r_a \quad (3)$$

where, p is the landslide occurrence probability at day 0 (i.e. the day of failure), r_0 the daily precipitation at day 0, and r_a the the antecedent daily precipitation for a specified period prior to day 0 (here 10 days). The respective equation demonstrates the triggering conditions for

landslides in the Wudu region based on the combination of 10-day antecedent precipitation and the daily rainfall (Fig. 5). In general, lower daily rainfall is required when higher antecedent rainfall conditions are present. After a certain threshold of antecedent rainfall the soil is so saturated, that no daily rainfall is required to cause landslides. Thus such an initiation is purely based on internal factors (such as positive pore water pressures) and not on external forces (such as additional precipitation). The results indicate, that a 10-day antecedent rainfall index of 20 mm is related to a 90% probability of landslides in the study area even

without any additional rainfall on the same day. The probability decreases to 50% and 10% with 17 mm and 13 mm, respectively. Similarly, an exceedance of a daily rainfall index value of 28 mm is related to a

90% probability of slope failures even without any antecedent rainfall. This probability decreases to 10% with a daily rainfall of 19 mm.

Figure 5 Rainfall thresholds for the Wudu region and related landslide occurrence probabilities (Bai *et al.* 2013b)

6.3 Spatio-temporal landslide analyses

A total of 122 landslides that have occurred between 1995 and 2002 were randomly selected for the creation of combined spatio-temporal landslide maps (Fig. 6) illustrating potential landslide scenarios for certain rainfall events. The daily rainfall model was applied to the selected landslides which relate to rainfall conditions that have a low, medium and high probability of causing slope failures; none fell into the category of very low occurrence probability (Fig. 6A). Figure 6B displays the spatio-temporal landslide map for rainfall conditions that have low probability of triggering landslides. Due to the re-classification using the matrix (Table 1), only very low, low and medium classes are present. This

map can be interpreted as the baseline susceptibility where areas are identified that might suffer landslides under frequently occurring rainfall conditions. Figure 6C is based on rainfall events with a medium probability to cause landslides. The spatial classification is the same as for the general susceptibility map (Fig. 4). Such rainfall conditions can be expected to occur regularly. The worst-case scenario is presented in Figure 6D. Under rainfall conditions that are related to a high probability of landslides, the susceptibility is much higher than in the previous maps. Large sections of the steep lower slopes in the study area have a high susceptibility and are thus likely to fail during extreme rainfall conditions.

Figure 6 Position and occurrence probabilities of landslides (A); spatio-temporal landslide maps for landslides for low (B), medium (C) and high (D) occurrence probability

7. Discussion

This study presents the combination of spatial and temporal landslide probabilities using a matrix approach. The landslide susceptibility map and the temporal landslide occurrence probability were estimated by well established methodologies, i.e. logistic regression and the daily antecedent rainfall model. The susceptibility map highlights the extreme landslide proneness of the area with its

high and steep mountain slopes which consist of weak lithological units. The rainfall thresholds show that both daily and antecedent rainfall play an important role for landslide triggering, however, daily rainfall has a larger influence. In comparison to other study areas, it was found that rainfall thresholds are relatively low (see <http://rainfallthresholds.irpi.cnr.it/> for an extensive selection of rainfall thresholds); however, they are in good agreement with the conditions observed in the Wudu region.

The susceptibility map and rainfall thresholds could already be used to raise awareness among the general public as well as to support regional decision-makers on risk management and spatial planning. In general, temporal and spatial landslide probabilities are regarded as separate products; in this study, however, an innovative approach is proposed in which a matrix is used to combine the aforementioned landslide probabilities, and to assign a combined spatio-temporal index value to the land surface. The resulting map therefore combines information on the environmental factors predisposing the area to landslides, as well as information on the triggering rainfall conditions. We are convinced that the combined spatio-temporal landslide maps better highlight the hot-spots of potential landslide activity and represent an added value to the use of susceptibility maps or rainfall thresholds alone. A particular strength of the proposed method is the scenario building which can be thought of as a representation of the outcomes of specific rainfall events. For areas, which feature a medium probability of failure under frequently occurring rainfall conditions, even small rainfall events can be expected to lead to scattered slope failures. The worst-case scenario map that shows susceptibility conditions for extreme rainfall events can be used to estimate the outcomes of rare storms causing widespread slope failures. Such scenarios could help to improve the communication of regional stakeholders and the general public by raising awareness towards the landslide hazards.

To improve the results of the presented research, further investigations of landslide-triggering rainfall conditions should be carried out. Currently, the antecedent daily rainfall is calculated by a simple decay factor which simplifies the storage of water in soils. Internal characteristics of soils, such as permeability and saturated soil water content, as well as external factors such as evapotranspiration are not reflected. Moreover, only limited rainfall data was available to this study. Additional weather stations and complex simulations of rainfall distributions including orographic effects of topography would help to calculate more precise landslide-triggering rainfall thresholds. Moreover, additional data for the

calculation of spatial landslide probabilities, in particular digital elevation data of higher resolution than the current 30 m pixels, would be desirable and could drastically improve the results of susceptibility modelling. It also must be questioned in which extent the rainfall thresholds and the susceptibility maps are valid for the future given that they are only based on a short period for which data were available and due to the fact that the ongoing economic growth in Western China leads to massive human impacts, such as land use changes, increased population pressure and large scale construction of infrastructures.

Table 2 Three examples of possible matrixes for deriving spatio-temporal index values. (a) matrix assigning fewer low probability index values; (b) matrix assigning more low probability index values; (c) matrix introducing a fifth probability class to highlight hot-spots

(a) Temporal		Spatial probability			
probability		Level 1	Level 2	Level 3	Level 4
Level 1		Class 1	Class 1	Class 2	Class 2
Level 2		Class 1	Class 2	Class 2	Class 3
Level 3		Class 2	Class 2	Class 3	Class 4
Level 4		Class 2	Class 3	Class 4	Class 4

(b) Temporal		Spatial probability			
probability		Level 1	Level 2	Level 3	Level 4
Level 1		Class 1	Class 1	Class 1	Class 1
Level 2		Class 1	Class 2	Class 2	Class 2
Level 3		Class 1	Class 2	Class 3	Class 3
Level 4		Class 1	Class 2	Class 3	Class 4

(c) Temporal		Spatial probability			
probability		Level 1	Level 2	Level 3	Level 4
Level 1		Class 1	Class 1	Class 2	Class 2
Level 2		Class 1	Class 3	Class 3	Class 3
Level 3		Class 2	Class 3	Class 4	Class 4
Level 4		Class 2	Class 3	Class 4	Class 5

We think that a matrix approach is very useful for the combination of spatial and temporal landslide probabilities, however, it must be noted that it is of course extremely sensitive to the classification of the input data. Classifications for both, susceptibility maps and rainfall thresholds may greatly vary from one study to another and no single classification standard exists. Instead, the classification is generally defined based on the goal of the study or the requirements of the user group for which it is prepared. More complex classification could be appropriate for experienced spatial planners while the general public could probably benefit more from more simple map products. Some possible matrixes to be used in future studies are visualised in Tables 2.

8. Conclusions

This study presents an innovative approach to carry out a semi-quantitative analysis of spatio-temporal landslide probabilities in the Wudu study area in western China. Based on a database on landslide causative factors and an inventory of historic slope failures, a susceptibility map is calculated by a GIS-based logistic regression which ranks areas according to their likelihood to produce slope failures. In particular areas with mudstones, siltstone and conglomerates on slopes steeper than 20° feature a high probability of failure. Landslide occurrence probabilities in relation to daily and antecedent rainfall are estimated using the antecedent daily rainfall model. Rainfall thresholds are relatively low and a 90% probability of landslides is given with a daily rainfall of 28 mm. A simple yet innovative and adaptable matrix-based methodology is applied to combine the spatial and temporal probabilities of landslides and to produce combined spatio-temporal landslide maps. Therein, the combination of areas of high spatial and temporal probabilities result in high combined index values, while the combination of low spatial and temporal probabilities results in low combined index values. A high spatial landslide probability combined with a low temporal probability results in a medium combined index value, and vice versa. Still, other matrix classification could be used to

meet the requirements of the users. The maps produced aim to raise awareness towards landslides hazards and to support regional decision. It can be expected that other researchers will apply a similar methodology to combine temporal and spatial landslide probabilities which are currently mostly put forward separately.

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