Mapping mountain torrent hazards in the Hexi Corridor using an evidential reasoning approach

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Abstract. The Hexi Corridor is an important part of the Silk Road Economic Belt and a crucial channel for westward development in China. Many important national engineering projects pass through the corridor, such as highways, railways, and the West-to-East Gas Pipeline. The frequent torrent disasters greatly impact the security of infrastructure and human safety. In this study, an evidential reasoning approach based on Dempster-Shafer theory is proposed for mapping mountain torrent hazards in the Hexi Corridor. A torrent hazard map for the Hexi Corridor was generated by integrating the driving factors of mountain torrent disasters including precipitation, terrain, flow concentration processes, and the vegetation fraction. The results show that the capability of the proposed method is satisfactory. The torrent hazard map shows that there is high potential torrent hazard in the central and southeastern Hexi Corridor. The results are useful for engineering planning support and resource protection in the Hexi Corridor. Further efforts are discussed for improving torrent hazard mapping and prediction.

1. Introduction

Water-related natural hazards such as landslides and torrent processes pose a threat to human life, property and infrastructure (Totschnig and Fuchs 2003; Balica et al., 2009). The hazard risk may increase due to continued socio-economic development (population increase, economic wealth, human activities in hazard-prone areas and urban development) and climate change (increase of heavy precipitation, changes in natural water cycles) (Turowski et al., 2009; Keiler et al., 2010; Mazzorana et al., 2012; Ronco et al., 2014). Disaster risk assessment is an important prerequisite to support the development of strategic adaptation and prevention measures to minimize torrent impacts (Ronco et al., 2014). Thus, the concept of risk represents the possibility of the occurrence of hazards (hazard) and their potential consequences (vulnerability) (Carter, 1992; Alexander, 2000; Kienholz et al., 2004).

The Hexi Corridor is a very important part of the Silk Road Economic Belt and a crucial channel for westward development in China. It is an engineering corridor and thus many important national engineering projects pass through the corridor, such as highways, railways, and the West-to-East Gas Pipeline. The Hexi Corridor is a densely populated area in the northwest of China and is also a cultural transmission path (Chen et al., 2003; Li et al., 2010a). The Hexi Corridor is in a transition zone between the alpine cold and extreme arid regions northwest of China. The oasis is dependent on a
series of inland river sources from precipitation and glacial run-off in the Qilian Mountains and groundwater. Mountain torrents frequently occur in this area. Approximately 96 water-related disasters occurred in the last thirty years of the last century in Wuwei city in the eastern Hexi corridor, causing hundreds of deaths and approximately one billion dollars in economic losses (Luo et al., 2005). The precipitation in mountain areas has clearly increased since the 1990s. The increasing extreme precipitation, intensity and frequency of extreme precipitation may exacerbate the risk of flooding and landslides (Li et al., 2010b). Therefore, mapping the risk of mountain torrents in the Hexi Corridor is a realistic need to support engineering and landscape planning and contribute to cultural heritage protection and disaster prevention.

Several methodologies have been developed to assess torrent risk. The choice of methodology largely depends on the analysis objectives (Ronco et al., 2014; Lepuschitz, 2015). As a preliminary study, the objective of this study is to provide a hazard map of torrent hazard occurrence, i.e., the physical environmental relative risk map. The related environmental factors including slope, vegetation fraction, river channel buffers, meteorological factors such as rainstorm days, maximum runoff discharge, flood disaster history, and expert knowledge were integrated using Dempster-Shafer theory within a Geographic Information System (GIS) framework.

2. Study area

The Hexi Corridor is located in northwestern China (Figure 1). It refers to the area west of the Yellow River in Gansu province. The Hexi Corridor is surrounded by the Qilian Mountains to the south, by the Mazun, Heli, and Longshou Mountains and the Badain Jaran and Tengger Deserts to the north, by the Wushao Mountains to the east, and by the Kumtagh Desert to the west (Zhang et al., 2016). It includes Jiuquan, Zhangye, Wu Wei, Jinchang, and Jiayuguan cities and approximately 19 counties such as Dunhuang, Subei, Sunan, Minle, Gulang, under the jurisdiction of Jiuquan, Zhangye, and Wu Wei cities, respectively. The total population is approximately 4,920 thousand.

The Hexi Corridor is in the convergence zone of monsoon and continental climates. It is characterized by its distinct cold and arid landscapes (glacier, alpine meadow, forest, crops and desert) dominated by climate and terrain. The altitude of the Hexi Corridor decreases from south to north. The altitude of most of the mountains in the south is greater than 4000 metres and the altitude of the alluvial and diluvial plain is between 1300-2500 metres. Along an altitude gradient, the precipitation decreases and the air temperature increases from alpine to northern plain. The annual mean precipitation in the Qilian Mountains is approximately 250 mm and mainly occurs in summer. The oasis in the plain area mainly relies on water resources from the Qilian Mountains.

The hydrogeological characteristics of the Hexi Corridor vary from the south to the north and can be divided into discrete geomorphologic units, including the piedmont alluvial plain, alluvial plain, and desert. The southern region of the basin has extensive faulting with underlying bedrock, where an aquifer comprises highly permeable cobble and gravel deposits 300–500 metres thick. From the northern edge of this diluvial fan, the aquifer becomes confined or semi-confined, 100–200 metres thick; it comprises interbedded cobble, gravel, fine sand, and clay. Farther north, the groundwater table becomes shallower. Additional details on the hydrogeological characteristics of the area can be found in Fan (1981) and Chen (1997).

The geological tectonic of the Hexi Corridor is a complex fault basin. The basement is cross cut into a block faulting system by a series of North-West-West, North-West and nearly East-West faults. The neotectonic movement in the southern Hexi Corridor, i.e., the Qilian Mountains northern piedmont, is very active. The mountains in this area rose rapidly and the piedmont depression basin continuously subsided. This formed the corridor plain with thick quaternary sediments. Quaternary sedimentary layers are approximately 700-1200 metres thick (Li and Xing, 1988). For stratigraphic lithology, bedrock dominates the southern high mountain and northern low-mid mountain regions. The lithology is mainly composed of sedimentary rock and pyrogenic rock. The former includes argillaceous sandstone, mudstone, clastic rock, quartz sandstone, and shale and the latter includes granite and diorite. Rock with developed fracture is exposed at steep positions. The bottom and lower
slope areas are generally covered with loess. Alluvial loess and gravel soil are generally distributed in the intermountainous basin and on the surface of the accumulational plain. Alluvial Gobi and gravel are widely distributed in the central area of the Corridor (Li and Xing, 1988; Liu et al., 2013).

Figure 1. Location of the Hexi Corridor.

3. Materials and methodology
Previous studies show that the annual precipitation and slope are the dominant factors for torrent hazard in the Hexi Corridor (Luo et al., 2005; Zhang et al., 2007; Wang et al., 2013; Liu et al., 2013). Thus, slope, precipitation, vegetation fraction, flow accumulation, and the standard deviation of elevation were combined using an evidence reasoning method based on Dempster-Shafer theory.

3.1. Materials
The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) version 2 data with a spatial resolution of approximately 30 metres, developed jointly by the United States National Aeronautics and Space Administration (NASA) and Japan’s Ministry of Economy, Trade, and Industry (METI), were used in this study. The ASTER GDEM2 is considered the highest resolution digital elevation model (DEM) among the freely accessible global DEMs (Arefi and Reinartz, 2011). It is available online through the Data Pool at the NASA Land Processes Distributed Active Archive Center (http://gdex.cr.usgs.gov/gdex/). The ASTER GDEM product is generated from automatic processing of 1.5 million ASTER Level-1A stereo pairs by applying stereo correlation methodology and covers land surfaces between 83°N and 83°S. The absolute vertical accuracy of ASTER GDEM is 20 metres at a 95% confidence level. Compared with the ASTER GDEM, the ASTER GDEM2 has significantly improved spatial coverage, horizontal resolution, horizontal and vertical accuracy (7-14 m), and water masking and includes an additional 260,000 ASTER stereo-pairs to supplement the voids and artefacts of ASTER GDEM (Tachikawa et al., 2011). The factors influencing torrent hazard, including the slope and the standard
deviation (SD) of the elevation, were derived from ASTER GDEM using ArcGIS software. The accumulated flow was derived from ASTER GDEM, and precipitation was used as a weight factor using the ArcGIS hydrology module.

The mean 5 to 9 month total precipitation data from 1980 to 2011, developed by the Data Assimilation and Modeling Center for Tibetan Multi-spheres, Institute of Tibetan Plateau Research, and the Chinese Academy of Sciences (ITPCAS) (Yang et al., 2010; Chen et al., 2011) were used in this study. It has a spatial resolution of 0.1° and a temporal resolution of 3 hours. The precipitation field was produced by combining the three precipitation data sets including 740 in situ observations collected from China Meteorological Administration (CMA) operational meteorological stations, Tropical Rainfall Measuring Mission (TRMM) satellite precipitation analysis data (3B42) for 1998-2008 (Huffman et al., 2007), and the Asian Precipitation-Highly Resolved Observational Data Integration Toward Evaluation of Water Resources (APHRODITE) data (Yatagai et al., 2009); GLDAS precipitation data for 1979-2010 were used to replace TRMM 3B42 data that were not available beyond 40° N.

The vegetation fraction with a 1 km spatial resolution used in this study was estimated using a dimidiate pixel model based on the MODIS (Moderate Resolution Imaging Spectrometer) 16-day composite Normalized Difference Vegetation Index (NDVI) product (MOD13A2).

Flood disaster history data were used to validate the result.

3.2. Dempster-Shafer evidence theory
Dempster-Shafer evidence theory is an extension of Bayesian probability theory and allows for the quantification and management of data uncertainty (Gordon and Shortliffe 1985; Lee et al. 1987). The basic assumptions of Dempster-Shafer theory are that gaps exist in the body of knowledge and that belief in a hypothesis is not necessarily the complement of belief in its negation. The basic concept of evidence theory is the frame of discernment, denoted by θ. The selection of θ depends on the known knowledge, the level of understanding and what we want to know. The computing elements of Dempster-Shafer theory are the power set 2 θ. The degree of belief in the evidence from a source (for example, torrent hazard) in support of torrent hazard is referred to as the mass (m) committed to that. The amount of mass is often referred to as an evidence measure. A mass can be expressed as a mass function that maps each element of the power set into a real number from 0 to 1, with a larger value indicating a higher level of “belief”. A mass function meets the following conditions:

\[
\begin{align*}
  m(\emptyset) &= 0 \\
  \sum_{A \in 2^\theta} m(A) &= 1
\end{align*}
\]

where Φ is the null set or an empty set and m(A) is a basic probability assignment (BPA) which represents the support for every subset, A.

3.3. Generating evidence
The related environmental factors include slope, vegetation fraction, accumulated flow, and the standard deviation of the elevation as evidence of torrent hazard. This evidence, or the degree of support to torrent hazard from each data source, includes two parts:

\[ M_j = W_j \times S_j \]

where W is the weight of variable i assigned by local expert using analytic hierarchy process (AHP) as shown in Table 1, and S is the standardization for variable i using the minimum and maximum values, except for the accumulated flow, as follows:

\[ S_r = \frac{V_r - V_{\text{min}}}{V_{\text{max}} - V_{\text{min}}} \]

The flow accumulation function of the ArcGIS hydrology module was used to calculate the accumulated flow based on ASTER GDEM data. The standardization of total precipitation over 5 to 9 months (mm) as an accumulated weight was used to calculate the accumulated flow. Then, the mean
accumulated flow within a 3 km × 3 km area was normalized using a symmetric membership function shape.

**Table 1. Factors influencing torrent hazard and their weights generated using AHP**

| Variable (i)                   | Commitment | Weight (W) |
|--------------------------------|-------------|------------|
| Slope                          | Belief      | 0.85       |
| Vegetation fraction (%)        | Disbelief   | 0.5        |
| Flow accumulation              | Belief      | 0.9        |
| Precipitation (5-9 month)      | Belief      | 0.9        |
| SD of elevation                | Belief      | 0.7        |

3.4. Combining the evidence

In general, the basic belief, or evidence, is represented by the mass function. The mass function generates a basic level of belief for each evidence source for the torrent hazard and then a system of combination is used to combine these basic beliefs to generate a total degree of belief for the torrent hazard. The Dempster-Shafer theory uses an orthogonal sum (⊕) to compute a total belief degree using this equation:

\[
m_i \oplus m_j(Z) = \frac{\sum_{X \cap Y = Z} m_i(X)m_j(Y)}{1 - k}
\]

where \( Z \) is a torrent hazard label and \( X, Y \) is an input data label. The sum extends over two labels whose intersection is \( X \cap Y = Z \). The set of intersections represent common labels of evidence. The \( m_i \oplus m_j(Z) \) are used to determine the combined mass and are then assigned to the torrent hazard label \( Z \).

\[
k = \sum_{X \cap Y = \emptyset} m_i(X)m_j(Y)
\]

where \( k \) is a normalization constant that corrects for any mass that was committed to the empty set (Φ) and indicates the extent of conflict between the two sources considered (Shafer 1976). \( k=0 \) indicates complete compatibility and \( k=1 \) indicates complete contradiction. A value between zero and one indicates partial compatibility.

The equations above provide a method to combine two basic probability assignment functions and can be used with any number of basic probability assignment functions through repeating the application of equations (4) and (5). The implementation of combined evidence was conducted using the belief module of IDRISI 14.01 software, a GIS and remote-sensing image-processing tool developed by Clark Labs (Worcester, MA), USA.

Last, three indicators of the degree of belief, degree of plausibility, and belief interval are used to qualify the risk of torrent hazard. The degree of belief is the total degree of belief of the torrent hazard. The degree of plausibility is the evidence failing to reject the torrent hazard. The belief defines the lower boundary of the support for torrent hazard whereas the plausibility function defines an upper boundary. The range of belief and plausibility is referred to as a belief interval or an interval of uncertainty.

4. Results and discussion

4.1. Torrent hazard map and uncertainty

The degree of belief for the torrent hazard derived from five variables using the evidential reasoning method shows the distribution of torrent hazard in the Hexi Corridor (figure 2). High belief means a high risk of torrent. The high degree of belief for torrent hazard with a small belief interval shows the small uncertainty of the decision-making results (belief interval is not shown). The result is in agreement with disaster history data. The uncertainty of the results is mainly due to the limited impact factors and subjective judgement in the expert scoring process as well as the accuracy, scale-mismatch, and simple linear standardization process of the evidence.
In previous study, the precipitation factor was generally combined directly with other factors. This may be less reasonable because the spatial locations of annual or seasonal total precipitation factors and torrent occurrences do not completely match. Precipitation not only directly acts on torrents but also acts through flow accumulation. The length of flow accumulation is dependent on the spatial scale. The spatial consistency of the relative high risk area with past disaster points shows that the flow accumulation factor was successfully combined in the evidential reasoning process.

Figure 2. The degree of belief for torrent hazard in the Hexi Corridor.

4.2. Characteristics of torrent hazard in the Hexi Corridor
As shown in Figure 2, the distribution of torrent hazard in the Hexi Corridor is consistent with the landform characteristics. The high-risk areas are mainly concentrated in the Qilian Mountains, especially the upstream Shiyanhe and Heihe Rivers in the central eastern Qilian Mountains. Most torrent related disasters are distributed along the piedmont transition zone where the area is vulnerable to flood because it is close to a densely populated area. In general, the torrent hazard in the Hexi Corridor is dominated by medium- and low-risk levels, which are very sensitive to local factors and human activity. Thus, the characteristics of torrent hazard in the Hexi Corridor require higher resolution mapping in the future.

For higher resolution and higher accuracy prediction for random- and local-scale torrent hazard in the future, efforts in three aspects should be strengthened. The first is high-resolution data. Terrain and vegetation maps are available from airborne remote sensing (LiDAR: Light Detection and Ranging, and optical image) or satellite remote sensing images at sub-meter resolution (such as the high spatial resolution satellite GF-2 in China). Higher resolution precipitation products are the scarcest for prediction of torrent hazard and should be focused on in the future through cooperation with the meteorological field. The second is determining the impact thresholds of multi-factors and the non-linear relationships of the effects. The last is the study of the mechanisms of torrent hazard with a systems perspective.
5. Summary

In this study, we proposed an evidential reasoning approach based on Dempster-Shafer theory to map torrent hazard and risk. The capability of this method was demonstrated by the application to mapping mountain torrent hazard in the Hexi Corridor. A torrent hazard risk distribution map for the Hexi Corridor was generated by integrating the driving factors of mountain torrent hazard including precipitation, terrain, flow concentration processes, and the vegetation fraction. Although limited factors were integrated and they have some uncertainty, this study is a useful exploration for mapping torrent hazard based on GIS and remote sensing data. The map shows that the pattern of torrent hazard risk is consistent with past disaster locations in the Hexi Corridor. It is useful for supporting engineering planning and resource protection based on the level of probable torrent events in different locations.

However, torrents and the closely related disasters of landslide and debris flow are not only closely related to lithology and geological structure but also to trigger factors such as earthquakes, rainstorms and human activities with great uncertainty and randomness. The uncertainty and randomness are the largest obstacles to disaster prediction, especially for medium- and low-risk torrent hazard in the Hexi Corridor. For higher resolution and higher accuracy prediction and mapping of torrent hazards in the future, higher resolution remote sensing data could play an important role in furthering our understanding of the mechanisms of torrent hazard.

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