Use of quantitative landslide hazard and risk information for local disaster risk reduction along a transportation corridor: a case study from Nilgiri district, India

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ORIGINAL PAPER

Use of quantitative landslide hazard and risk information for local disaster risk reduction along a transportation corridor: a case study from Nilgiri district, India

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Abstract The objective of analyzing hazard and risk in an area is to utilize the result in selecting appropriate landslide risk reduction strategies. However, this does not happen always, and most often results of the hazard and risk analysis remain at an academic level. The under or non-utilization of results in pre-disaster planning could be due to several reasons, including difficulties in understanding the scientific content/meaning of the models, and lack of information on the practical significance and utility of the models. In this study, an attempt is made to highlight the uses of hazard and risk information in different landslide risk reduction strategies along a transportation corridor in Nilgiri, India. At first, a quantitative analysis of landslide hazard and risk was made. The obtained information was then incorporated in risk reduction options such as land use zoning, engineering solutions, and emergency preparedness. For emergency preparedness, the perception of the local Nilgiri communities toward landslide risk was evaluated and simplified maps were generated for the benefit and understanding of end users. A rainfall threshold-based early warning system was presented, which could be used in risk awareness programs involving public participation. The use of quantitative risk information in the cost-benefit analysis for the planning of structural measures to protect the road and railway alignments was also highlighted, and examples were shown how the transport organizations could implement these measures. Finally, the study provided examples of the utility of hazard and risk information for spatial planning and zoning, indicating areas where the landslide hazard is too high for planning future developments.

Keywords Landslide · Transportation corridor · Risk reduction · Community-based disaster management program · Nilgiri

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1 Introduction

Landslide hazard and risk information is generated for a variety of objectives within the framework of landslide risk management (Fig. 1). Landslide risk management essentially involves identification, estimation, and evaluation of the risks, implementation of risk reduction options, and balancing the different components of cost in an acceptable way (Crozier 2005). The information used in risk management itself is dynamic as indicated in Fig. 1, where environmental changes due to global change and resulting reactions in ecosystems, combined with expected changes in socio-economic development, lead to adjustments in land use in areas that are exposed to mass movements. These hazards also have domino effects, for example, the effect of land use change such as deforestation on creating more severe landslide hazards. The effects of these changes in hazard and risk patterns need to be incorporated into disaster risks management strategies even at stake-holder levels.

Within the risk assessment framework shown in Fig. 1, the estimated risk needs to be evaluated by comparing the output of the risk analysis against values of judgement and risk

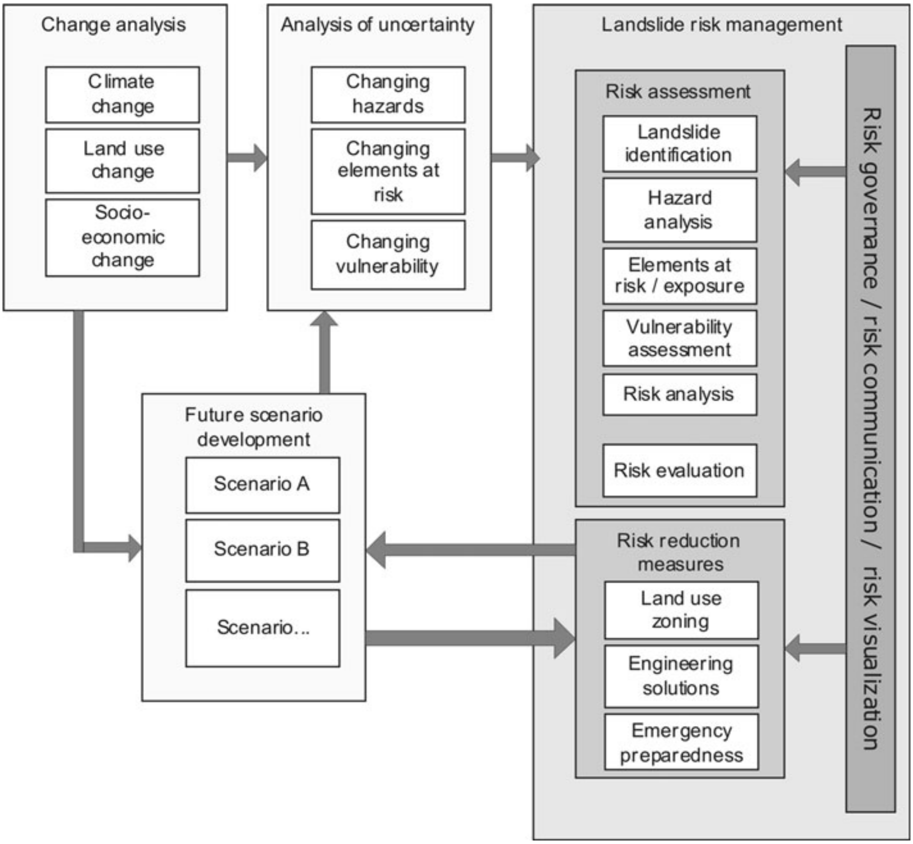

Fig. 1 Framework for landslide risk management (based on JTC-1 Technical committee on landslides and CHANGES 2011), including the evaluation of changes in hazard and elements at risk patterns for future development, and the associated uncertainties

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tolerance criteria to determine whether the risks are low enough to be tolerable (Fell et al. 2005). For example, in case of risk to life, the communities assess risk from a given landslide as acceptable or non-acceptable by evaluating the losses against the benefits that they obtain in the particular location (Bromhead 1997; AGS 2000). Such evaluations require interplay of various organizations where the judgement takes into account political, legal, environmental, regulatory, and social factors. Assessment of all these factors for evaluation of risk is beyond the scope of a geoscientist who carries out risk analysis. But, for the benefit of the end user, one can illustrate the use of the obtained landslide hazard and risk information in various risk reduction measures for the optimal management of landslide risk.

Once the risk analysis is completed for an area, the next step of risk management is to use the hazard and risk information to take measures to reduce risk to the communities living in the area or to the population passing the area along the transportation lines. In case of landslides, the objective of analyzing hazard and risk in an area is to utilize the result in selecting appropriate landslide risk reduction strategies. However, this does not happen always, and most often results of the hazard and risk analysis remain at an academic level. At least in India, though landslide studies have been carried out for many years, yet their direct application in land use planning and pre-disaster management is not well recognized. Under or non-utilization of results of hazard and risk analysis could be due to several reasons, including difficulties in understanding the scientific content/meaning of the models, and lack of information on the practical significance and utility of the models. Thus, in order to make the results usable, it is important for geoscientists to specify their practical significance and utility in the field. This will certainly lead to more acceptance and application of the results by planners and stakeholders.

Crozier (2005) listed nine different approaches to mitigate landslide risk. These approaches essentially work toward either reducing the probability (the temporal, the spatial, and the size) of occurrence of hazard in a given location by means of various mitigation options or reducing the vulnerability of elements at risk such as through improvements of the physical built-up environment by making them more resistant to the possible landslide impact. Risk mitigation can also be carried out either by reducing the amount of elements at risk in hazard areas such as by relocation or by increasing risk awareness among the people at risk through education. The nine approaches mentioned in Crozier (2005) can be grouped into three strategies: land use zoning, engineering solutions using cost-benefit analysis for the design of structural risk reduction measures, and emergency preparedness.

In this paper, the above-mentioned strategies of hazard and risk information in risk reduction are treated. For emergency preparedness, the perception of the local Nilgiri communities toward landslide risk is evaluated and simplified maps are generated for the benefit and understanding of end users. A rainfall threshold-based early warning system is presented, which could be used in risk awareness programs involving public participation. Quantitative risk information is also used for the planning of structural measures to protect the road and railway alignments, and examples are shown how the transport organizations could implement these measures. Finally, hazard and risk information can also be used for spatial planning and zoning, indicating areas where the landslide hazard is too high for planning future developments.

2 Study area

The study was carried out along a transportation corridor of a 22 km^2 area encompassing a 24-km-long section of a road and a 17-km-long section of a railroad (Fig. 2). The road is a

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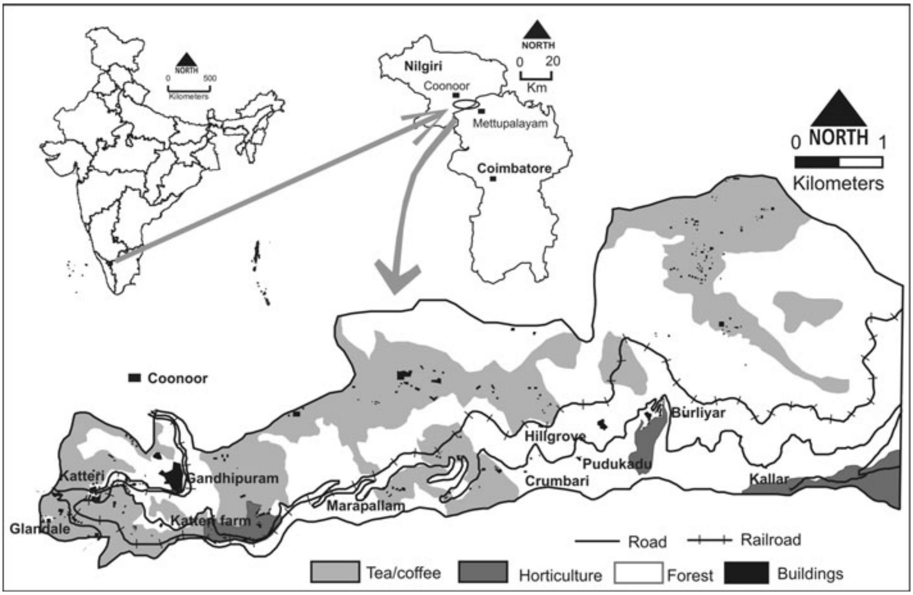

Fig. 2 Location of the study area

national highway (NH-67), and the railroad is declared by UNESCO as a "world heritage railway route". Both form part of the main transportation lines connecting Mettupalayam to Coonoor in the state of Tamil Nadu. The geo-environmental characteristics of the study area and the type of elements at risk present are discussed in detail in Jaiswal et al. (2010a, b, 2011a, b).

Tea plantation forms the main land use type. There are only a few settlements, with Burliyar, Gandhipuran, and Katteri being the major residential settlements. There are also small residential units within the tea estates (Fig. 2). A field survey carried out in 2008 reveals that the area is inhabited by 6,784 people. These includes 1,479 families consisting of 2,675 young males (13–60 years), 78 old males (>60 years), 2,582 young females, 84 old females, and 1,365 children (<12 years). Most (88 %) of the household heads are manual workers engaged in the tea and horticulture (spice garden and plant nursery) plantation. Their average income is less than US$ 100 per month.

3 Landslide hazard and risk information

The approach used to estimate landslide hazard and risk along transportation corridors is presented schematically in Fig. 3. Various analyses were performed to quantify landslide risk along the road and the railroad and the surrounding areas. A Gumbel analysis was carried out to determine the frequency of landslides on cut slopes and on natural slopes for certain units of the transportation line (Jaiswal et al. 2011a). Logistic regression analysis was carried out to model the susceptible areas to landslides on natural slopes (Jaiswal et al. 2010b). Rainfall threshold analysis was used to estimate the temporal probability of landslides, and magnitude-frequency analysis to obtain the probability of landslide size (Jaiswal and van Westen 2009). These data were combined in an analysis of landslide

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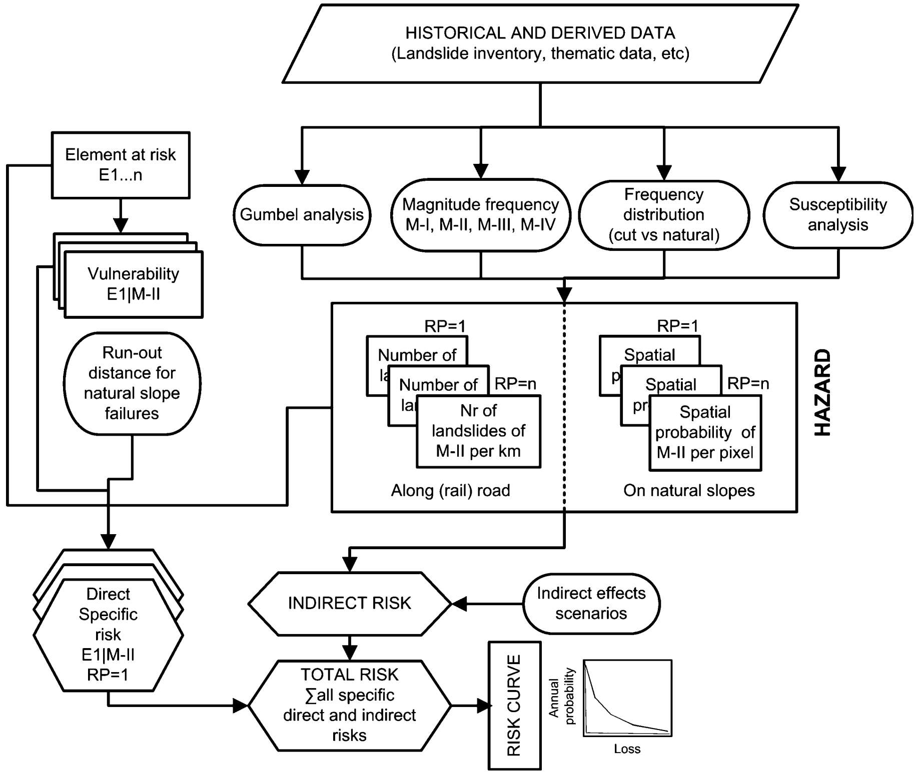

Fig. 3 *Flow diagram* showing the process adopted to obtain landslide hazard and risk information

initiation hazard on cut and natural slopes. Landslide run-out analysis was carried for landslides on natural slopes. Landslide vulnerability was established for landslides with different magnitudes and for different elements at risk. Landslide hazard and risk estimation was done using landslide events that occurred between 1987 and 2007, and the results were validated using landslides that occurred in 2008 and 2009. As a final output, direct risk was quantified for properties (alignments, vehicles, buildings, and plantations) and people (commuters and residents) and indirect risks due to the traffic interruption.

The detail description of the method used and the results can be found in Jaiswal and van Westen (2009); Jaiswal et al. (2010a, b, 2011a, b). In this paper, only the use of the quantitative hazard and risk information in different risk reduction options is discussed in detail.

4 Planning risk reduction strategies

The ultimate goal of any risk analysis is to reduce the risk to the communities by using different mitigation options. The choice of the type of option depends on the preference of the decision-makers, who are normally expected to use hazard and risk information to arrive at a conclusion. The approach required for planning risk reduction strategies is

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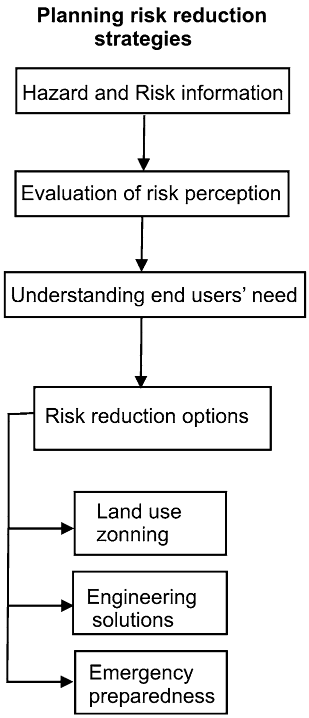

Fig. 4 *Flow diagram* showing the process required for planning risk reduction strategies

presented in Fig. 4. The different components of Fig. 4 are described in detail in the subsequent sections.

4.1 Evaluation of risk perception

For a successful risk mitigation, involvement of local communities in the decision-making is equally important (Pearce 2003). If local communities are ignored, then chances of providing reasonable solutions to disaster-related problems are often decreased, and in many instances, the decisions and actions taken by the planners are challenged, thus creating an atmosphere of conflict, delay of the mitigation plans, and increase in mitigation cost. Thomas (1995) presented a number of ways of involving the public in the decision-making process such as through public meetings, surveys, advisory committee, etc. If communities are to be involved in the planning processes, then it becomes necessary to understand the perception of the local population and their needs for managing risk.

The following paragraphs summarize the findings of the landslide risk perception surveys that were carried in the Nilgiri area. The objective was to understand the perception of the people toward landslide risk, which will later help in selecting appropriate strategies of risk reduction in the study area. The perception to landslide risk depends on the cultural perspective and background of the people. Harmsworth and Raynor (2005) discussed five situations which, in general, contribute to an increase in people's perception to landslide risk. These include perception of risk formed from loss of natural resources, from impacts on economic assets and production loss, from experience of an actual damaging landslide event, from damage of cultural features or icons, and from education or community participation. In the Nilgiri area, people are aware of landslide risk because landslides occur

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very frequently in the area and cause substantial damage to life and property. In the study area, perception of risk is formed mainly from experience of the actual damaging landslide events in recent past (e.g., in 1993, 2006 and 2009), from the loss of production and business due to road blockage and from the risk awareness program undertaken in the schools and local communities.

For the perception study, a questionnaire survey was used in order to understand the local communities' interest in the landslide disaster-related problems. The survey was carried out at 12 locations (settlements) in the Nilgiri area, and the local population was interviewed in groups. The targeted groups had a different socio-economic status in the communities, such as laborers, businessmen, servicemen, and school children. The locations were selected in such a way that one group represented people who had witnessed or experienced landslides in 2009, one group of people located in landslide hazardous area, one group of people who had witnessed landslides in past, one group of people who have never experienced landslides and are located in safe areas, a group of people involved in businesses (e.g., shop owners at Katteri and Burliyar), and a group representing educated school children. The questionnaire was designed to obtain information on peoples' perception about landslide risk, their pre-disaster preparedness, methods for transferring warning information, and strategies they use to reduce and mitigate landslide risk. The same set of questions was used for interviewing people in all locations. Since the questions were in English, we personally interpreted the questions for their understanding and selected answers that represented the common opinion in the groups. The objective behind surveying people with different economic and educational status and having recent or past or no landslide experiences is to observe the change in the perception of people to landslide risk as a result of recent loss or impact of landslides.

The important findings of the questionnaire survey are:

1. Most people of the Nilgiri area are aware of landslide disasters, and they accept the fact that their area is prone to landslides,
2. They are aware of the cause of landslides (i.e., very high rainfall), and they know that the period between October and December is the most problematic,
3. They are not able to indicate the areas that could be the a potential source of landslides (susceptible slopes),
4. People do not appreciate/understand technical terms such as landslide disaster readiness, disaster preparedness, susceptibility, probability of death, etc.,
5. Most of the people have lived in the study area all their life and their ancestors for many generations, and in spite of the fact that they have experienced or witnessed landslide disasters, they do not want to leave their native place,
6. People tolerate the risk because of certain benefits such as working in nearby tea plantations, running businesses along the road, etc.,
7. People perceive landslides as an "act of God," and they believe that only wrong doers will be affected,
8. They have no emergency preparedness plans and insurance coverage of properties for a landslide disaster,
9. They depend on the local government and local organizations such as rescue operation unit, a non-governmental organization, for post-disaster help and mitigation,
10. The low economic status of most communities does not permit them to carry out additional investment for reinforcement of their houses in order to protect them from landslide damages, and

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11. People agree to provide services and land for installing monitoring devices for landslide warning; for example, drillings were carried out at nine locations in the Katteri area on the private property for instrumentation for landslide monitoring.

The study indicates that irrespective of their economic status, people are conscious about the landslide problems and they consider that the local administration is responsible to take up necessary measures to make their houses safer from landslide disaster. People want timely information on expected landslides in their area and the know-how to reduce and mitigate landslide risk. In many cases, it was observed that people are ignorant about what to do and no to do during a landslide disaster. From the interview, it is evident that most people lack knowledge about different precautionary measures to be followed during a high rainfall event, except for schoolchildren and people who have taken part in the disaster management programs conducted by the rescue operation unit.

Besides local people, authorities such as railway, road, and local administration were also contacted in order to understand their perception to landslide risk. The authorities view landslides as a persistent problem in the Nilgiri area. They are willing to find out feasible solutions to the landslide problems in order to safeguard the local population from landslide disaster.

4.2 Evaluation of end users' need

Landslide hazard and risk information are the outcome of scientific analysis of various geo-environmental and landslide damage data, and normally, these can be best interpreted by the geo-scientists who developed the models. If such results are to be used by non-scientific communities, then in addition to the scientific content, it is essential to provide results in a format which non-scientific users can understand. There can be different types of end users depending on the area of interest and the type of landslide problems. Therefore, it is important to identify potential end users and find out their requirements and later present the results in terms that the user can use.

In the study area, several end users are defined as indicated in Table 1, which also summarizes the requirements and purposes of different end users. Table 1 clearly indicates that end users can be geo-scientists (Geotechnical unit), engineers (Railway and Highway units), businessmen (tea estates), or common people with little or no education. Their requirement varies depending on the type of work they do. Therefore, information should be provided according to their needs in order to make the hazard and risk maps understandable and applicable to the end users.

4.3 Risk reduction options

4.3.1 Land use zoning

Land use zoning is the most economical and effective means of reducing future landslide losses. For planning land use zoning strategies, we require information on the distribution of past landslides (inventory) and areas vulnerable to future landslides (susceptibility/hazard). Information on past landslides can be obtained from the landslide inventory map. The inventory map helps to have accurate perceptions of where mass movements have occurred that posed threats to the communities. Such maps can provide valuable information for land use planning. For example, recurrent damage from landslides can be avoided by evacuating areas that continue to have slope failures, and frequent landsliding

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Table 1 Different end users and their requirements

End user	Requirements	Purpose
Railway unit and Highway unit	Information on volume of debris expected on the (rail) road, information on specific kilometer sections where frequency of landsliding would be more, data on future losses	Planning of funds and manpower for (rail) road clearance, prioritization of remedial work of clearance, cost-benefit analysis for engineering works
Geotechnical unit (a landslide investigation cell of Government of Tamil Nadu)	Recent susceptibility or hazard maps with additional information on potential debris flows run-out distances, demarcation of safe and unsafe areas	To issue clearance certificate for safe building construction,
Tea estates	Information on landslide prone areas, including debris flows	To protect tea plantations and to apply engineering solutions such as slope flattening. plantation, drainage, etc
Rescue operation unit 9, a non-governmental organization)	Requires simplified and user friendly hazard and risk maps	To educate local population about potential landslide risk through community-based disaster management programs
Local people	Information on damaging landslides. timely warning of landslides, risk awareness	To reduce property losses and fatalities

areas can be prioritized for landslide monitoring and mitigation. A large scale inventory map showing slope failures of different time periods can be used to infer the evolution of landslides with time or to monitor changes in the area of landslides, which may pose danger to communities located nearby.

Landslide inventories can be used by different end users to derive information specific to their work and requirements. Figure 5a shows an example of the type of information that the railway and road maintenance units can derive from the inventory. For example, the railway unit may not be interested in knowing the location of the landslide scars on hill slopes rather they will be interested to know which section of the railroad was affected. The figure shows the longitudinal section of the railroad, for example, between km-20 and km-21 and the sections that were affected by debris from cut and natural slopes. Such information can be used to locate sections where landslides have occurred in past and where they are expected to occur in future. If GIS is used, then the multi-temporal information on landslides can be used to observe the active sections and the sections where landslides occur repeatedly thereby prioritizing the mitigation work. This information can further help to calculate the length of retaining wall needed to contain debris from the adjacent cut slopes.

Figure 5b shows the type of landslide information that the geotechnical units, tea estates, and local communities can derive from the landslide inventory, depending on their area of interest. The area showing paths of debris flowslides and overbank erosion can be avoided for any future development, and immediate actions must be taken to protect those slopes from further erosion in order to minimize the risk to properties located nearby (e.g., Fig. 5c).

When interpreting a landslide inventory map, one should remember that all landslides shown in the map may not persist and with time unstable slopes eventually get stabilized

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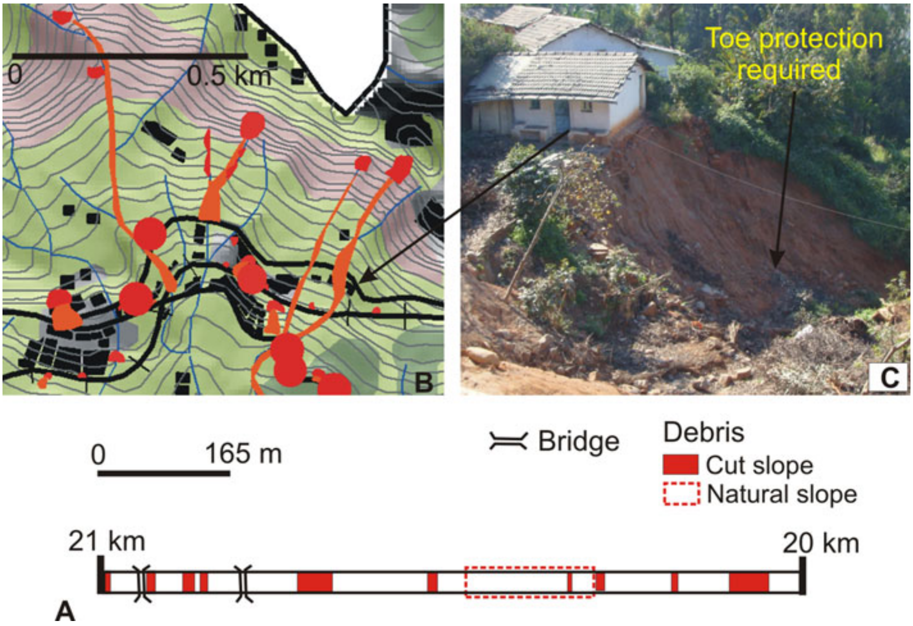

Fig. 5 Use of landslide inventory for risk reduction planning (see text for explanation)

due to natural or man made actions. Also, if the map is not complete then one should be careful in interpreting areas where no landslide is shown. For the optimal use, the inventory map should be updated after every triggering event and for this institution appropriate for the work should be identified. It is advisable to use such maps in GIS.

The information on landslide susceptibility/hazard can be used for planning future developments. The hazard provides information on areas prone to landslides in future, including the type of landslides, number of landslides and volume of debris expected (Jaiswal et al. 2011a).

Figure 6a shows the type of information that a geotechnical unit can derive from the landslide susceptibility map and use it for issuing clearance certificates for safe building construction. Here, susceptibility maps are often used in defining a building permit system encompassing both permits for construction a building in a particular location and the type of building (building codes). The permit system restricts or regulates new developments, such as construction of roads, buildings, irrigation, etc., in landslide susceptible areas. It can carry instructions such as constructions are only allowed in low landslide susceptible areas whereas appropriate slope treatments are mandatory in moderate susceptible areas, and no constructions are allowed in high susceptible areas. The map can be presented with three classes based on the relative likelihood of occurrence of landslides. The areas having a higher proneness to landslides are shown in red. Orange represents areas where chances of future landslides are lesser than red and green are the safe areas or areas having very low chances of occurrence of landslides. The red areas should be avoided for construction of new buildings, utility centers and communication infrastructures. Such areas can be used as open space, parks, woodland and recreation. In orange areas, it should be mandatory to carry out basic stabilization works before taking up any building projects. The green areas are relatively safe for construction of buildings. It should be noted that the orange or green

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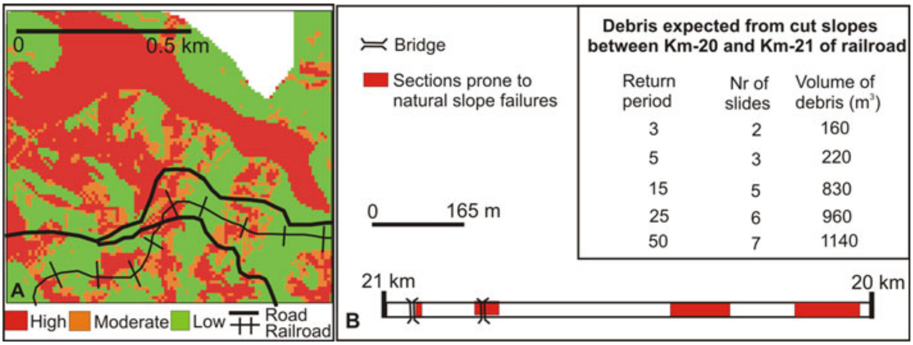

Fig. 6 Use of landslide susceptibility and hazard information for risk reduction planning (see text for explanation)

susceptible areas can be affected by debris flows from upslope areas and therefore when interpreting the map the landslide travel distance (run-out) should be considered.

It should be noted that the map shown in Fig. 6a is applicable for the present land use and environmental condition, and if the land use changes or new landslide information is available, the susceptibility map should be updated. Other than geotechnical unit, the susceptibility map can be used by the rescue operation unit, tea estates and the local communities to identify areas that are potential for future landslides within their area of interest. For example, such maps can be posted on a display board in the center of the communities for warning against potential landslide disaster. The susceptibility map in combination hazard information, which shows the likelihood of occurrence of landslides within a given time period, can be used for a more rational planning of land use for a given design life of the project.

Figure 6b shows the type of information that the railway and road maintenance units can derive from the result of the hazard analysis. The figure shows the sections of the railroad between km-20 and km-21 prone to potential landslides derived based on the result of the susceptibility and the run-out model (Jaiswal et al. 2011a, b). Further information on the number of landslides and the total volume of debris expected in different return periods, expressed in years, from cut slopes can be obtained using the hazard information (Jaiswal et al. 2011a). This information can be used to estimate the minimum or maximum funds and manpower required to mitigate landslide disaster in a budget period. For example, an event with a 50-year return period (annual probability of 0.02), will result in a maximum damage and thus require the maximum allocation of funds and manpower. The results can also be used to identify sections where relatively more landslides can occur, given the threshold exceedance within a rain gauge area, and thus facilitates timely transfer of equipments to the nearest location for early clearance of the (rail) road. The results can also help in prioritizing engineering solutions for the sections of the (rail) road where the frequency of landslides are expected to be more.

4.3.2 Engineering solutions

Engineering solution is the most direct and costly strategy for reducing landslide risk (Dai et al. 2002). It involves either correction of the underlying unstable slopes using methods such as modification of the slope geometry by excavation or toe fill, use of retaining structures, internal slope reinforcements, surface drainage, etc. or controlling of the

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Fig. 7 Slope stabilization measures: **a** grass turf combined with retaining wall and **b** concrete retaining wall

landslide movement to reduce its impact on the elements at risk located down slope. In practice, before considering any engineering solution for hazard mitigation, its feasibility study in the form of cost-benefit analysis is often carried out. For such studies, information on risk forms an important input.

Below we provide an example where we demonstrated the use of the obtained risk results in selecting the cost-effective engineering solution for mitigating cut slope failures along the road and the railroad. The example only provides a rough estimate of the costs based on the available information, and the actual value may differ depending on the specification of the measures, the extent of the area to be treated and implementation cost.

4.3.3 Cost-benefit analysis using risk information

The quantitative risk analysis provides the total annual loss, which is the basic parameter required to carry out such cost-benefit analysis. In this example, three engineering measures are considered:

- Grass turf—the use of grass turf is not very common in the study area but in one experiment (Fig. 7a), the feasibility of a grass turf in landslide mitigation along a road cut was tested. The process involves modification of the slope below the friction angle, which in this case taken as 30° angle, and then use of turf to cover the slope. The advantage of this method is that it does not require periodic maintenance over a long period, and since it involves flattening of slope, it is more reliable in containing shallow mass movements. As a disadvantage, this method may not be feasible if the slope is steep and where flattening of the slope is difficult. The average cost of this measure in 2009 is US$ 6.5/m^2, including the costs of flattening of slope.
- Concrete retaining wall—this measure involves constructing a concrete retaining wall at the toe of the cut slope to stabilize slope failure. Figure 7b shows the concrete retaining structure constructed to stabilize a cut slope failure. The method is suitable along the road where availability of space permits construction of a retaining wall; however, along the railroad, the method is not very common due to the space limitations. The average design life of a retaining wall is 15 years. The advantage of this method is that it also does not require continuous maintenance. But, as a disadvantage since the maximum height of the structure is 3 m, it may not be suitable for containing a large landslide. The average cost of this measure in 2009 is US$ 69/m^3.
- Boulder gabion wall—this is the most common mitigation measure used in the study area. It is of low cost, the average cost is US$ 1.07/m, and is effective for small slope failures. The method involves stacking of boulders in a wire mess, and the structure is

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used as a retaining wall for providing toe support. The structure has a design life of 2 years.

In cost-benefit analysis, the cost is the one-time investment costs of the project and maintenance costs that arise over the lifetime of the project. The maintenance cost includes costs of the annual maintenance of the measures against landslide damage and clearance of debris overtopping the retaining structures. For this analysis, the costs for maintenance are considered to be 1 % of the project cost. It is assumed that these costs will increase with 5 % each year. Benefits are taken as loss reduction, that is, the savings in terms of direct and indirect loss due to cut slope failures, which are estimated as the total annual loss. The total annual loss is about US$ 164,500, which include the loss of US$ 128,400 along the railroad and US$ 35,100 along the road.

Finally, costs and benefits have to be compared under a common efficiency criterion in order to be able to derive at a decision. Net present value (NPV) is one of the criteria, which is most commonly used in cost-benefit analysis (Crosta et al. 2005). Costs and benefits arising over the life time of the project are discounted and the difference taken, which is the net discounted benefit in a given project life. The sum of the net benefits is the Net present value. If the NPV is positive (i.e., benefits exceed costs), then a project is considered feasible to implement.

In order to perform the analysis, several assumptions were made: the project will take an investment period of 4 years for turf for mitigating a 3.5 km of scars along the railroad, 2 years for turf for mitigating a 1.5 and 2 km of scars along the railroad in different sections, 2 years for a concrete retaining wall and 2 years for a gabion wall for mitigating all 2.1 km of scars along the road. It is also assumed that after mitigation no major slide will take place.

The cost-benefit analysis was performed for six scenarios considering the maintenance costs and investment periods as given above and 10 % interest rate. NPV was taken as the criteria for comparison of feasibility of different measures and was calculated for a period considering the life time of the measures, that is, 15 years for turf and concrete retaining wall and 2 years for gabion wall. The six scenarios are:

- Scenario #1-the grass turf is applied for treating many landslide scars between km-10 and km-26 of the railroad. The benefit is US$ 128,400, which is the total annual loss due to cut slope failures along the railroad and the cost is US$ 455,000 for a combined scar length of 3.5 km.
- Scenario #2-the grass turf is applied for treating many landslide scars between km-10 and km-13 of the railroad, which is the maximum hazard section. The benefit is US$ 52,360, and the cost is US$ 195,000 for a combined scar length of 1.5 km.
- Scenario #3-the grass turf is applied for treating many landslide scars between km-14 and km-26 of the railroad. The benefit is US$ 76,040, and the cost is US$ 260,000 for a combined scar length of 2 km.
- Scenario #4-the grass turf is applied for treating many landslide scars along the road. The benefit is US$ 35,100, and the cost is US$ 273,000 for a combined scar length of 2.1 km.
- Scenario #5-a concrete retaining wall is constructed for treating many landslide scars along road. The benefit is US$ 35,100, and the cost is US$ 484,550 for a combined scar length of 2.1 km.
- Scenario #6-a gabion retaining wall is constructed for treating a 2.1-km-long section with many landslide scars along the road. The benefit is US$ 35,100, which is the total annual loss and the cost is US$ 6,800.

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Table 2 Cost and benefit of different slope treatment measures

Scenarios	Type of mitigation measures	Cost of mitigation measure (US$)		Benefit (US$)	Investment period (years)	NPV (US$)	Remarks
		Per unit	Total cost				
Scenario #1	Grass turf	$6.5/m^2$	455,000	128,400	4	184,100	Feasible
Scenario #2	Grass turf	$6.5/m^2$	195,000	52,360	2	123,500	Feasible
Scenario #3	Grass turf	$6.5/m^2$	260,000	76,040	2	201,200	Feasible
Scenario #4	Grass turf	$6.5/m^2$	273,000	35,100	2	−51,300	Not feasible
Scenario #5	Concrete retaining wall	$69/m^3$	484,550	35,100	2	−250,700	Not feasible
Scenario #6	Gabion wall	1.07/m	6,800	35,100	2	44,300	Feasible

The cost of the treatment of cut slope scars was obtained based on the data (per unit cost) provided by the highway and the railway office. Table 2 shows the result of the six scenarios. The remark indicates whether the project is feasible or not feasible. If NPV is positive, that is, benefits exceed costs then the project is considered feasible. Along the road, the NPV was less than zero for turf (scenarios #4) and concrete retaining wall (scenarios #5) thus suggesting that these measures are not profitable. The first three scenarios (#1, #2, #3) along the railroad are profitable mitigating measures, and therefore, these can be tested. The analysis suggests that financially it is recommendable to apply grass turf for stabilizing unstable scars between km-14 and km-26 of the railroad (scenarios #3). The result also suggests that since the NPV of scenario #1 is positive and comparable to scenario #3 and in scenarios #1, there is an advantage of mitigating all landslide scars along the railroad; therefore, it is more reasonable to use scenario #1 instead to scenario #3 for mitigating landslides along the railroad. But, the feasibility of these scenarios from geotechnical, environmental and engineering aspect should also be considered. For example, scenario #1 may not be technically feasible due to steep terrain rather scenario #3 is more technically viable.

Similar calculations can be performed for different slope stability measures using results of risk models. However, it may be noted that before selecting any mitigation measure, the actual cost-benefit analysis has to be performed by professionals, using the actual estimated values of costs of measures, maintenance costs, investment period, interest rates, etc. One type of measures may not be suitable for the entire area; rather, several different combination of mitigation measures can be considered depending on the type of elements at risk such as some slopes can be stabilized using grass turf while some using retaining wall or even cost-benefit analysis of option such as alteration of bridges, bioengineering solutions, measures like soil nailing, shot creating, etc. can be carried out. Nevertheless, in all analysis, information from risk models will form an important input.

4.3.4 Emergency preparedness

Emergency preparedness denotes the ability of a community to put into action established plans and procedures (Crozier 2005). This strategy tends to reduce the risk by increasing awareness among the public with an aim to timely respond to the warning when the disaster strikes. Preparedness essentially includes public awareness education programs and understanding of warning system for timely response. There can be different types of early warning systems for landslide forecast such as those for an individual landslide to

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warn people about the movement of specific landslide based on movement sensors, etc., or those for communities or organizations for small areas (using simple thresholds and rain gauges) or those for large areas (like a weather prediction for very high rainfall which could be potential for triggering landslides). The most cost-effective means of an early warning system is those based on rainfall/landslide relations through the use of a rainfall threshold (Keefer et al. 1987; Aleotti 2004). Warning system can provide information on when landsliding would occur and this in conjunction with hazard maps can delineate potentially hazardous areas (Dai et al. 2002). The public awareness education programs are often carried out under the community-based disaster management program (CBDMP) which includes participatory mapping exercises, mock drills for emergency response, etc. (Chen et al. 2006).

4.3.5 Development of a landslide early warning system

One of the most cost-effective measures to reduce landslide risk to the communities in the Nilgiri area is the implementation of a simple landslide early warning system, in which the communities themselves play a major role. Our work published in Jaiswal and van Westen (2009) and Jaiswal et al. (2010b) on rainfall thresholds can be a good basis for the development of such an early warning system.

In several countries, rainfall thresholds have been used to forecast rainfall-induced landslides, particularly in the USA (San Francisco Bay area) (Keefer et al. 1987; Baum and Godt 2010) and Hong Kong (Chan et al. 2003). The warning system is composed of several components, including establishment of rainfall-landslide thresholds, rainfall forecasting methods, real-time rainfall monitoring and an automated computing system for evaluation of warning. The system is essentially based on a quantitative precipitation forecast using remote sensing data and a large network of automated rain gauges to issue warning message on threshold exceedance. The capabilities of warning system rely on the empirical threshold model which can be based on various precipitation measurements such as antecedent rainfall, rainfall intensity and duration, cumulative rainfall and duration, normalized rainfall, etc. The details of the types of threshold models used all over the world can be found in Guzzetti et al. (2008). Landslide early warning systems can also be designed for individual landslides that have intermittent activity, for example, using extensometers to monitor slope deformation, or using cables with vertical rods to detect debris flows. However, in the study area, nearly all of the major landslides are first event failures, and therefore, the installation of such types of early warning systems is not feasible.

The warning system proposed here considers daily rainfall as there are no rain gauges that continuously record rainfall data. The model uses threshold rainfall, rainfall forecasts, probability of occurrence of landslides given the threshold exceedance, and hazard and risk models to issue an early warning of rainfall-induced landslides. The threshold is derived from the empirical relationship of 5-day antecedent and daily rainfall required to trigger landslides. The 24-hour rainfall forecast can either be based on the weather forecast by the Indian Meteorological Department (IMD) or it can be inferred from the rainfall and weather condition. Advanced techniques of rainfall forecasting such as the Doppler radar are not available for the study area. The warning system will essentially require the manual measurement of daily rainfall from different rain gauges and the comparison of the 5-day cumulative and daily/forecast rainfall with the threshold value to determine the threshold exceedance. The calculation of threshold exceedance can be performed automatically in an excel sheet, or on paper.

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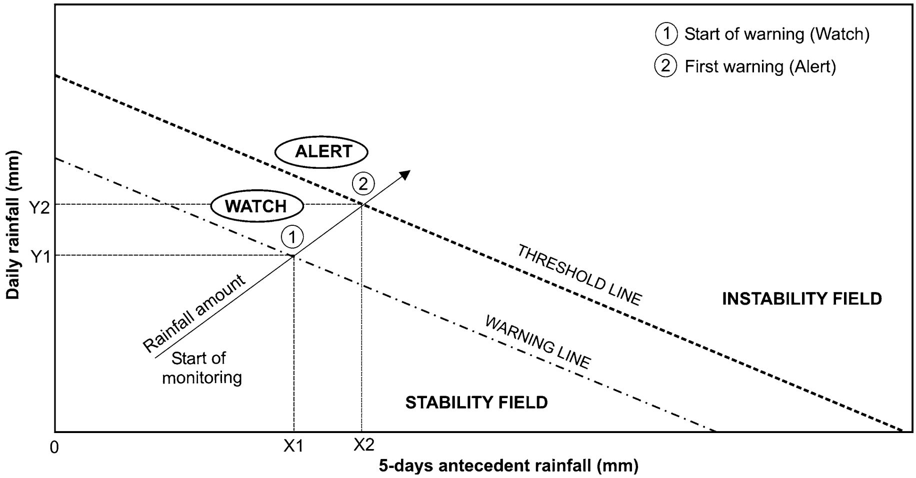

Fig. 8 Criteria that can be used to issue warning of rainfall-induced landslides based on rainfall threshold

Figure 8 shows the criteria that can be used to issue different levels of warning of rainfall-induced landslides. The first warning line can be introduced slightly below the actual threshold line, that is, a limit which, if exceeded, activates the start of the warning procedure (Aleotti 2004). When the recorded rainfall (X1Y1) crosses this limit at Phase-1 it starts up the warning procedure. At this stage, 'Watch' warning can be issued cautioning the people that a critical condition of slope failure has reached and further rains may trigger landslides. From here, threshold variation can be continuously monitored using different values of forecast rainfall. At this stage use of forecast, rainfall is important in order to observe the trend of the rainfall in the next 24-hour hours. When rainfall in the next 24-hour is expected to exceed the threshold line or the current rainfall touches the threshold line (X2Y2) then Phase-2 warning (Alert) can be issued. The warning will alert the community about the possible occurrence of landslides. On further monitoring whether the rainfall is expected to exceed further then the communities should be cautioned of major landslide events and instruct them to be prepared for immediate evacuation.

The warning for evacuation is not feasible using this system because it is very difficult to predict the precise location of landslide initiation based only on threshold information. The exact location of landslides is important if people are to be evacuated. In fact after the 'Alert' warning, the people should be on the alert and start looking for signs of instability, and then only evacuate. Since exceedance of the threshold indicates that the condition conducive for landsliding has set in, after the 'Alert' warning people should start working with the disaster preparedness plan so that the loss can be minimized.

4.3.6 Operating procedure of the warning system

Figure 9 describes the conceptual operating procedure of the warning system. Its practical application is yet to be tested in the field. The warning procedure gets activated when the recorded 5-day antecedent and previous day rainfall passes the warning line. At this stage (Phase-1), a general warning 'WATCH' can be issued at least 12 hours in advance informing people that the rainfall condition is critical and slope failures may result if a similar rainfall condition continues. Warning should also contain information about

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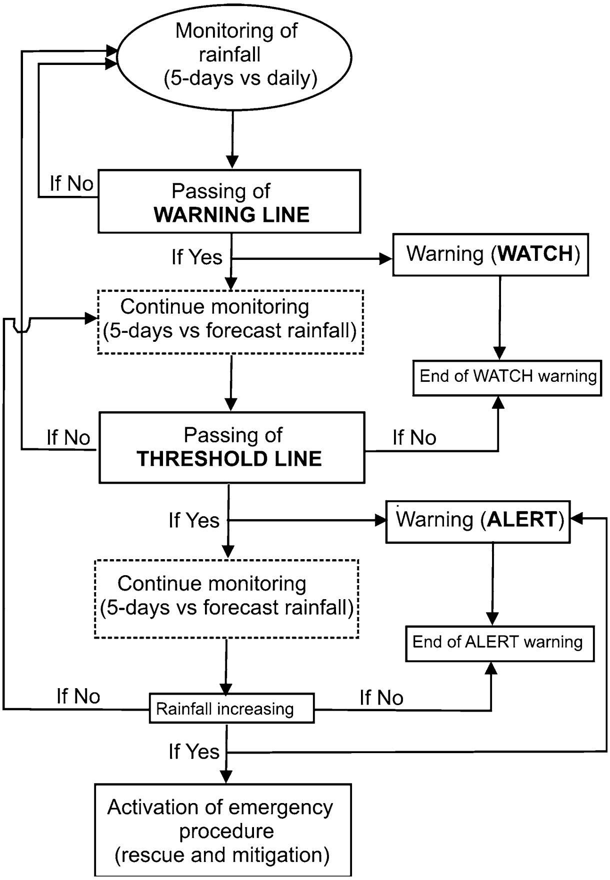

Fig. 9 Operating procedure of warning system based on rainfall thresholds

emergency readiness, safe place for evacuation and precautions to reduce risk to life. This phase provides time to the authorities to disseminate information to the public and make equipment available for the potential disaster.

After Phase-1, continued monitoring of the threshold rainfall is carried out using different values of rainfall forecasts. During this time, additional information is gathered such as the probability of occurrence of landslides given the exceedance (see Jaiswal and van Westen 2009) in a given area. If the forecasted rainfall or the measured rainfall at a certain time touches or exceeds the threshold line then the 'ALERT' warning (Phase-2) should be issued informing the people about the specific areas where landslides can occur based on the obtained hazard information. At this stage, people are advised to look for indications of landslides such as opening cracks, unusual sounds (rumbling/cracking sound of debris) and be prepared for evacuation if similar rainfall conditions persist. This phase gives relatively less time to the people and the authorities to react.

After Phase-2, variation in thresholds is continuously monitored using both measured and forecasted rainfall. At this time, risk maps can be consulted and specific hazardous areas can be outlined. This phase requires very rapid assessment of specific hazard and risk because of the small reaction time and because of being in the instability field. If the

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rainfall decreases below the threshold line then the 'ALERT' warning can be withdrawn and if it increases further then the 'ALERT' warning remains and the authorities can simultaneously activate the emergency procedure such as rescue and mitigation.

Figure 9 shows a general operating procedure that can be used by any end user. However, depending on specific requirement and the type of risk to be reduced, the operating procedure and the type of warning may differ. For example, for the railway, even a small cut slope failure along the railroad will be disastrous and therefore the railway unit would like to use thresholds of small landslide events (i.e., events triggering less than 15 landslides) for issuing the 'ALERT' warning and stopping the train services. In contrast, for the small landslide events, the highway unit can keep the road open for small vehicles but close the road if rainfall passes the threshold for the entire route (i.e., events triggering >15 landslides). Table 3 summarizes the activities of different end users during the warning phase. These activities are highlighted in order to ensure maximum reduction of risk due to landslides in the study area. In case of the road, stopping of all vehicles and closure of the road is advisable only if the 'ALERT' warning is for the large event. This is because for small events, the chances of occurrence of landslides after the exceedance of the threshold are less than 50 % but for the large events the chances is 73 % (Jaiswal and van Westen 2009).

4.3.7 Limitation of warning system and needs

Warning systems for potential rainfall-induced landslides are technically feasible; however, operational warning systems are practical only where the elements at risk make such systems cost-effective and the population is willing to respond to the warning issued (Baum and Godt 2010). There can be several reasons which make the implementation of warning systems difficult. These include limited resources, lack of data on hazard and risk zones, barriers to rapid communication in remote areas, lack of public awareness about potential landslide risk, and confusion about what landslide warnings means and what actions to be taken when a warning is in effect. Besides these practical difficulties, uncertainties in the warning system further make its implementation difficult. Frequent false alarms (warnings that are not followed by landslides) or landslides that occur without warning decrease the trust of the population in a warning system.

Development of a clear warning language and instructions that are appropriate to the locality and its population are essential for the successful implementation of an early warning system. Publications on language and statements for different levels of warning are available (e.g., Keefer et al. 1987). Warning should essentially include instructions such as "does and don'ts" during an imminent landslide disaster, indications/signs to recognize a landslide (e.g., cracks, rumbling/cracking sound of debris) and indication of safe areas. It should also include a description of the expected hazard, delineation of the affected area, appropriate actions, how long the warning is valid and contacts for more information.

For the study area, the following text of the warning could be used for the 'WATCH' category if the local communities are to be warned:

> Due to continuous rainfall in Area-A of Coonoor subdivision, there is a possibility of occurrence of landslides in the area (or along the road/railroad section between km-Xa and km-Xb) if the rainfall continues to remain the same or increases further. People living in this area are advised to be cautious, be prepared with emergency supply kit, should watch for any pre-landslide indications and inform their family

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Table 3 Type of end users and their activities during warning phase

User	Threshold for warning	Area of warning	Type of failure	Warning phase and type of warning issued		Activities and remarks
				Watch	Alert	
Railway unit	$R_T = 66 - 0.93\ R_{5ad}$	East of Burliyar	Cut slope	Active vigilance and patrol	Stop train services	Resume services after end of the ALERT warning
	$R_T = 165 - 1.32\ R_{5ad}$	Around Hillgrove	Cut slope			
	$R_T = 250 - 1.5\ R_{5ad}$	Around Marapallam	Cut slope			
	$R_T = 230 - 1.32\ R_{5ad}$	West of Runneymede	Cut slope			
	$R_T = 220 - 0.61\ R_{5ad}$	Entire railroad			Close railroad	Mobilization of man power for the railroad clearance
Highway unit	$R_T = 66 - 0.93\ R_{5ad}$	East of Burliyar	Cut slope	Active vigilance and patrol,	Stop public buses and mass transport vehicles, only small vehicles allowed to pass but with caution,	Emergency vehicles on standby at different locations, deployment of bulldozers at safe locations,
	$R_T = 165 - 1.32\ R_{5ad}$	Around Hillgrove	Cut slope			
	$R_T = 250 - 1.5\ R_{5ad}$	Around Marapallam	Cut slope	Police check post on high alert		
	$R_T = 230 - 1.32\ R_{5ad}$	West of Runneymede	Cut slope			Resume services after end of the ALERT warning
	$R_T = 220 - 0.61\ R_{5ad}$	Entire road	Cut slope		Stop all vehicles, road closed	Mobilization of man power for the railroad clearance
Local communities	$R_T = 210 - 0.54\ R_{5ad}$	Study area	Natural slope	Inform family members, collect emergency supplies, first aid, etc.	Be on high alert, Start looking for signs of instability, and then only evacuate	Evacuate schools and other buildings with many people that are located in potential hazard zones,

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Table 3 Type of end users and their activities during warning phase

User	Threshold for warning	Area of warning	Type of failure	Warning phase and type of warning issued		Activities and remarks
				Watch	Alert	
Local administration	$R_{\mathrm{T}} = 210 - 0.54\ R_{5\mathrm{ad}}$	Study area	Natural slope	Issue of 'WATCH' warning message	Issue of 'ALERT' warning message	Activation of emergency procedure (rescue and mitigation)

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members about the nearest safe ground. Keep listening to your news media for further information.

For the 'ALERT' category following text can be adapted:

A warning of a level 'Alert' is hereby issued to people living in Area-A. Due to continuous rainfall, the potential for landslides has increased and people should be aware that a similar rainfall in past had triggered slides. Persons in the warning areas should be prepared to move to safer ground immediately if similar rainfall condition continues to exist for next few hours. Watch out for signs of landslides till rainfall subsides. Keep listening to your news media for further information.

It is important that the warning message should reach to the people concerned within a stipulated time. The risk perception survey indicates that people prefer electronic media (television) more than radio or internet. It is advisable that an alternate medium of warning should be established in case of power failure, which is common during very heavy rains. One way is to use short messaging service of mobile telephone or through representative identified in each community for transferring of the warning messages.

4.3.8 Public awareness and education program

For successful implementation of warning systems, and other risk reduction measures, a public education program is essential to ensure that residents of landslide prone areas understand the landslide hazard, its causes, the appropriate precautions, and actions that should be taken to prepare for and respond to landslide events. There are several ways to make people aware of the potential landslide disasters. More commonly, it is done without involving the public directly in the awareness program such as by issuing instructions through print or electronic media, representatives or social workers, pamphlets, etc. This type of approach is fast and cost-effective but does not ensure that people will actually receive the information. Alternatively, more effective methods are those that involve the public directly. Through community participation programs, people can be educated interactively about the potential hazard, appropriate actions required on warning, alternate safe routes, first aid, etc. Even the risk perception surveys suggested that the local populations want more interactive awareness programs in order to learn about the risk reduction methods.

Community-based disaster management programs (CBDMP) can be grouped into different types depending on the way the community is involved (Chen et al. 2006). A description of all the types of CBDMP and their implementation is beyond the scope of this study; however, two disaster preparedness approaches are presented here that have been tested in the study area:

- Participatory mapping exercises, which help in educating local people on the potential landslide hazard, alternative routes for evacuation and disaster preparedness, and
- Mock drills, which include training of government officials and local population on search and rescue and first aid.

The earlier risk awareness programs were based on historical knowledge of landslides in the area, but with the availability of the hazard and risk maps, it is now possible to incorporate knowledge of future risk scenarios. Information from the hazard and risk assessment should be included in the participatory mapping exercises and landslide experts should be involved in the CBDMP.

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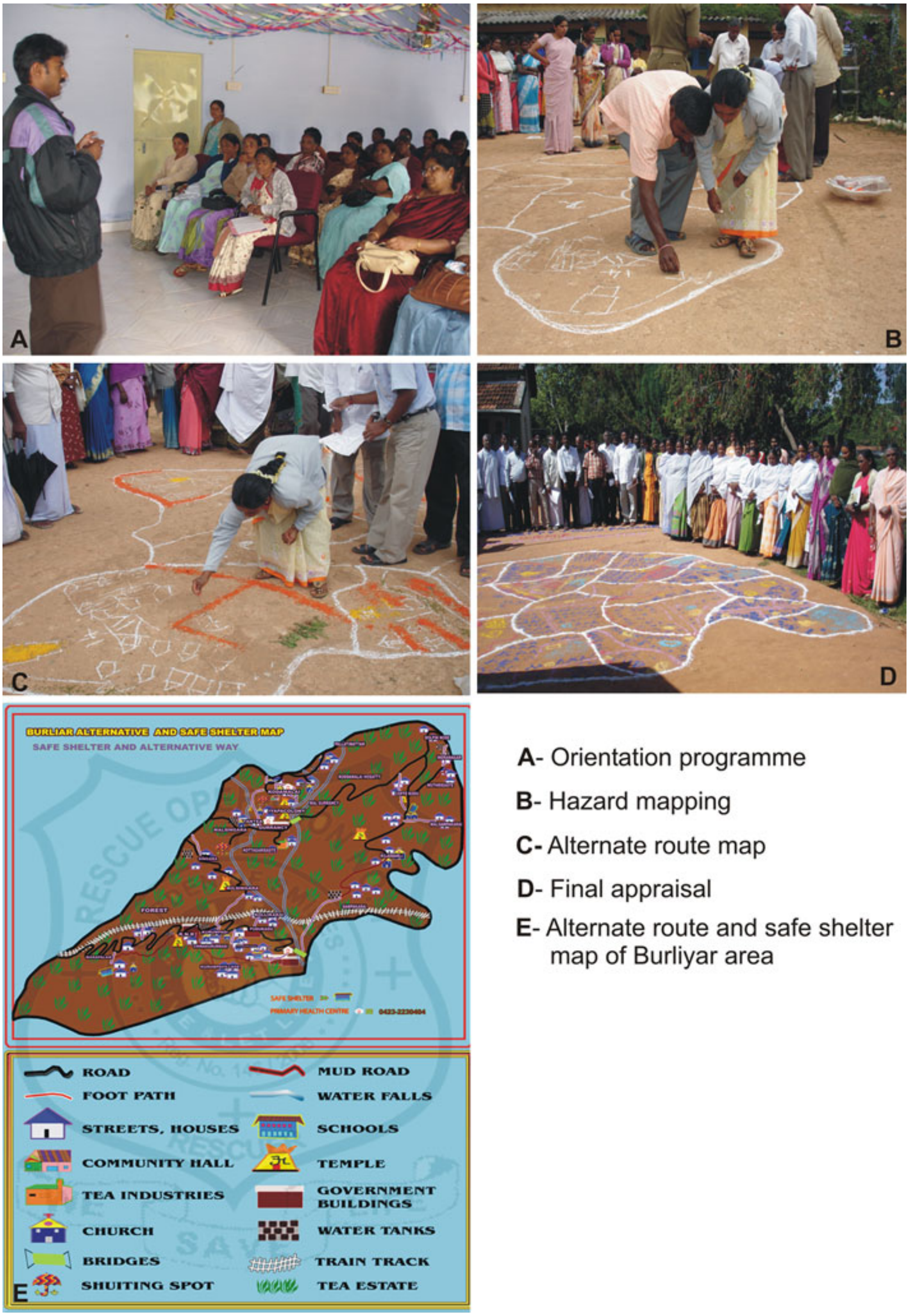

Fig. 10 Participatory mapping exercises (photographs provided by the rescue operation unit, Coonoor)

Participatory mapping: The aim of these exercises is to obtain the level of knowledge of the local individuals and communities about the nature of the threat, and its potential impact, the options for reducing the risk or impact, and how to carry out specific mitigation

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measures. It is also aimed to obtain views from the community about their disaster experiences, collect information about past landslide events and their impact, determine aspects that contribute to vulnerability, and determine feasible risk reduction scenarios and their risk reduction strategies in an informal, flexible and relaxing atmosphere. The important activities include mapping of hazard and risk, vulnerabilities, safe and alternative routes, and the preparation of a village level disaster management plan solely based on public experiences.

The following activities are required for the participatory mapping exercises:

- Orientation: At first stage, an orientation program is conducted where people can be briefed about the importance of the exercise, about landslide phenomena, a warning system, risk preparedness, their responsibilities, etc. It is expected that when the people understand the goal of the exercise and benefits, they will participate more actively. Figure 10a shows photograph of the orientation program that was conducted in the study area by the rescue operation unit of Coonoor. The first challenge here is to bring people together for the participation. The most effective way is to involve local administration at the beginning. This gives a sense of trust and importance to the program if the officials are involved and the people take the event more seriously. Other incentives, such as free refreshment, certificate of attendance, etc. are provided, which also ensures people participation. In fact the local government allocates funds to hold such programs at a regular interval.
- Mapping landslide hazard and risk: in this stage, people are asked to draw a sketch map of their locality and identify the landslide areas based on their experiences. The mapping helps those who have not experienced landslides such as new residents and the younger generations to understand the landslide problems in their area. The mapping can be done on paper, or using large prints of high resolution photographs on which people can recognize buildings, roads and fields. However, it is also possible to make these maps by drawing them with chalk on the ground, which has a better visibility and gives the opportunity for more interaction. At this stage, potential landslide hazard and susceptible areas can also be added based on the information from the hazard and risk analysis described in the previous chapters. Information should also be exploited to identify areas at risk for the run-out of debris flows in addition to areas where landslides may initiate. Figure 10b shows a field photograph of the mapping exercise undertaken by the local community in the study area.
- Mapping alternative routes and safe shelters: the third stage consists of identification of alternative evacuation routes and safe shelter places drawn by the people based on their local knowledge of the terrain. At this stage, landslide experts are required to evaluate the places and routes drawn by the people for the potential landslide risk. Figure 10c shows a field photograph of people drawing evacuation routes in their locality, and Fig. 10e shows the paper representation of these routes and safe shelters prepared by the people living in the Burliyar community.
- Problem appraisal and developing solutions: At this level, the community should develop a list of problems based on the above exercises. The community under guidance of experts should discuss the problems and probable solutions or ways to lessen the impact. It is important that the community identifies its own strategies using its own reasons and mitigation goals and outlines a framework for a community-based disaster management plan for risk reduction.

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Fig. 11 Mock drills (photographs provided by the rescue operation unit, Coonoor). Search and rescue (**a**–**d**) and first aid (**e**–**f**)

- Identification of representative: The final step in this process is to identify a representative within each community who can liaison with the local officers and emergency management personnel during pre- and post-disaster phases.

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Mock drills: The purpose of mock drills is to provide the local community with the basic skills that they need to respond to their community's immediate needs in the aftermath of a landslide disaster, when emergency services are not immediately available. After discussing with the local people and understanding their needs, the planning team can set up courses targeted at search and rescue, first aid and time management. Trained emergency personnel, including local fire-fighters and emergency medical service personnel, supervise the mock drill. Figure 11 shows field photographs of the mock drill organized at Coonoor on 27 July 2007.

5 Discussion and conclusions

The perception study highlighted different aspects of how people perceive landslide risk. People's perception changes and often increased if they have experienced damaging landslide events or if their properties are at risk, for example, after the 2009 landslide event, the owner of a Katteri property was willing to invest in the mitigation measures even without support of the government. Unlike flood and earthquakes, which have widespread consequences, landslides have localized effects; therefore, they are viewed more as a personal problem rather than a societal issue. The study showed two aspects of people's perception of landslide: first, they perceive landslide as a natural disaster, and most of the communities are aware of the landslide phenomena, its causes, period of occurrence, etc. Such perception arises mainly from their past experiences and education. Second, most people show ignorance about the threat and do not have pre-disaster preparedness plans. The second aspect is more common in the society because of the low economic status of the people and also from the fact that people are unaware of the threat from landslide initiating in areas located away from their dwellings. The economically 'poor' people, such as laborers are more concerned about issues such as health, housing, employment, education, household incomes, etc., than the environmental or disaster issues. Similar perception is seen in other part of the world (e.g., in New Zealand) where livelihood takes precedence over the environmental issues in poorer section of the society (Harmsworth and Raynor 2005).

Risk perception can also be learned over time through education and collaborative learning through community participation. The study showed that in most cases, people are unaware of what to do and not to do during a landslide disaster and also they are ignorant about the stability of their surrounding areas. Disasters like 2009 can be averted if the people become aware of the potential threat. Therefore, efforts must be made to bring pre-disaster preparedness studies into the school curriculum. In fact, school plays an important role in the risk awareness process. Through awareness arising at the school level, not only the most vulnerable part of the population (children) is reached, but through the children also their parents can be targeted. School children can also be taught to look for signs of potential instability (cracks, disrupted vegetation, blocked drainage) and report these. Once the perception of communities and individuals of landslide risk is understood, it is then easier to facilitate and plan remedies and solutions to lessen the risk.

The study demonstrated some of the important uses of hazard and risk information in planning risk reduction measures. In land use zoning, the general concept of the means of reducing risk is to relocate the existing elements at risk from high hazard zones to hazard free areas. However, practice has shown that this is very difficult to implement. Therefore, land use zoning is more appropriate for defining restrictive zones where new constructions are not allowed. In fact relocation of elements at risk is often not a real option because

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people do not want to relocate, unless the local authorities offer economically much more favorable alternatives. To make this option viable, the strategy should involve the affected stakeholders and the public in the planning process because the public is more likely to comply with the policies if they feel that they have some ownership of the process and have input into the plan. Furthermore, it is often the public who have to meet the cost of risk reduction measures.

Engineering solutions, such as restoration and slope stabilization works, construction of drainages, etc., are often used to reduce landslide risk by minimizing the probability of landslide occurrence. Landslide mitigation using engineering solutions is expensive and is generally suitable for a few known unstable slopes as it is difficult to delineate the precise location of potential landslides and areas affected by potential debris flows at a catchment scale. Nevertheless, the type of engineering solutions to be adopted is decided after evaluating the cost-benefit ratio of the desired solution and for that information from quantitative risk models are used. In this study, the cost-benefit analysis suggests that engineering solutions can be used to mitigate landslide hazard but it is to understand that complete removal of hazards is not always feasible (Stanganell 2008); therefore, effort must be toward reducing the vulnerability through awareness and warning system so that the coping capacity of the communities' can be increased.

In this paper, an early warning system for landslides was presented to reduce the loss of life due to disastrous landslides. The use of an empirical threshold is a fundamental element of the proposed warning system. However, it is important to understand that the empirical relationship between rainfall and landslide occurrence is a simplification of the actual phenomena (Aleotti 2004).

Effective implementation of the proposed warning system requires significant resources. These include personnel for rainfall monitoring at all rain gauges, updated landslide hazard and risk maps, means to disseminate warnings, experts to interpret results, scientific rainfall forecasts, etc. Most of these resources are not always readily available, and therefore, efforts are needed first to establish the operational infrastructure and involvement of dedicated professional staff in order to provide reliable early warning of landslides. In case if it is not possible to create a separate infrastructure at this stage with dedicated staff for the early warning then it is advisable to implement this system at the community level. The railway and highway units can use thresholds for cut slope failures and their rain gauges to issue warning to regulate traffic movement while the local communities can use the rainfall information from the tea estates located within their community to issue warning locally. No doubt the latter case requires participation of the local communities, and therefore, CBDMP is so important.

Our responsibility, as a geological community, should not be confined to the production of scientific maps and models but also to ensure their practical utility through active participation in educating planners and engineers about the types of hazard facing their communities (Howell et al. 1999). Through participatory exercises and trainings, it is possible to make the communities aware of potential hazard areas, to strengthen their capability to resist landslide disasters and to develop an organization in order to carry out risk reduction actions. However, according to the rescue operation unit, the involvement of local communities in the exercises and mock drills is a challenging job as people are often not willing to participate. It was evident in the 2007 CBDP that after orientation, only few people accepted to act as victims and few tried to react according to the situation, but many people stood and watched the incident as spectators only.

Based on the knowledge gained in this study, we conclude that for risk reduction more priority should be given to increasing awareness among people through CBDMP about the

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potential danger and ways to reduce risk. The frequency of CBDMP activities should be increased such that all communities living in landslide prone areas should be educated, for at least once.

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References

Aleotti P (2004) A warning system for rainfall-induced shallow failures. Eng Geol 73:247–265

Australian Geomechanics Society and Sub-committee on landslide risk management (AGS) (2000) Landslide risk management concepts and guidelines. Aust Geomech 35(1):49–92

Baum RL, Godt JW (2010) Early warning of rainfall-induced shallow landslides and debris flows in the USA. Landslides 7(3):259–272

Bromhead EN (1997) The treatment of landslides. In: Proceedings of institution of civil engineers. Geotech Eng 125:85–96

Chan RKS, Pang PLR, Pun WK (2003) Recent developments in the landslip warning system in Hong Kong. In: Proceedings of the 14th Southeast Asian geotechnical conference, Balkema, Lisse, The Netherlands

CHANGES (2011) The CHANGES network (Changing Hydro-meteorological Risks-as Analyzed by a New Generation of European Scientists). www.itc.nl/changes

Chen LC, Liu YC, Chan KC (2006) Integrated community-based disaster management program in Taiwan: a case study of Shang-an village. Nat Hazards 37:209–223

Crosta GB, Frattini P, Fugazza F, Caluzzi L, Chen L (2005) Cost-benefit analysis for debris avalanche risk management. In: Hungr O, Fell R, Couture R, Eberthardt E (eds) Landslide risk management. Taylor and Francis, London, pp 517–524

Crozier MJ (2005) Multiple occurrence regional landslide events in New Zealand: hazard management issues. Landslides 2:247–256

Dai FC, Lee CF, Ngai YY (2002) Landslide risk assessment and management: an overview. Eng Geol 64:65–87

Fell R, Ho KKS, Lacasse S, Leroi E (2005) A framework for landslide risk assessment and management. In: Hungr O, Fell R, Couture R, Eberthardt E (eds) Landslide risk management. Taylor and Francis, London, pp 3–25

Guzzetti F, Peruccacci S, Rossi M, Stark CP (2008) The rainfall intensity–duration control of shallow landslides and debris flows: an update. Landslides 5:3–17

Harmsworth G, Raynor B (2005) Cultural consideration in landslide risk perception. In: Glade T, Anderson MG, Crozier MJ (eds) Landslide hazard and risk. Wiley, London, pp 219–249

Howell DG, Brabb EB, Ramsey DW (1999) How useful is landslide hazard information? Lessons learned in the San Francisco Bay region. Int Geol Rev 41(4):368–381

Jaiswal P, van Westen CJ (2009) Estimating temporal probability for landslide initiation along transportation routes based on rainfall thresholds. Geomorphology 112:96–105

Jaiswal P, van Westen CJ, Jetten V (2010a) Quantitative assessment of direct and indirect landslide risk along transportation lines in southern India. Nat Hazards Earth Syst Sci 10:1253–1267

Jaiswal P, van Westen CJ, Jetten V (2010b) Quantitative landslide hazard assessment along a transportation corridor in southern India. Eng Geol 116:236–250

Jaiswal P, van Westen CJ, Jetten V (2011a) Quantitative assessment of landslide hazard along transportation lines using historical records. Landslides 8(3):279–291

Jaiswal P, van Westen CJ, Jetten V (2011b) Quantitative estimation of landslide risk from rapid debris slides on natural slopes in the Nilgiri hills, India. Nat Hazards Earth Syst Sci 11:1723–1743

Keefer DK, Wilson RC, Mark RK, Brabb EE, Brown WM, Ellen SD, Harp EL, Wieczorek GF, Alger CS, Zatkin RS (1987) Real-time landslide warning during heavy rainfall. Science 238:921–925

Pearce L (2003) Disaster management and community planning, and public participation: how to achieve sustainable hazard mitigation. Nat Hazards 28:211–228

Stanganell M (2008) A new pattern of risk management: the Hyogo framework for action and Italian practise. Socio-Econ Plan Sci 42(2):92–111

Thomas JC (1995) Public participation in public decisions. Jossey-Bass, San Francisco, CA