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An integrated approach for evaluating the effectiveness of landslide risk reduction in unplanned communities in the Caribbean

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Abstract
Despite the recognition of the need for mitigation approaches to landslide risk in developing countries, the delivery of 'on-the-ground' measures is rarely undertaken. With respect to other 'natural' hazards it is widely reported that mitigation can pay. However, the lack of such an evidence-base in relation to landslides in developing countries hinders advocacy amongst decision makers for expenditure on ex-ante measures. This research addresses these limitations directly by developing and applying an integrated risk assessment and cost-benefit analysis of physical landslide mitigation measures implemented in an unplanned community in the Eastern Caribbean. In order to quantify the level of landslide risk reduction achieved, landslide hazard and vulnerability were modelled (before and after the intervention) and project costs, direct and indirect benefits were monetised. It is shown that the probability of landslide occurrence has been substantially reduced by implementing surface-water drainage measures, and that the benefits of the project outweigh the costs by a ratio of 2.7 to 1. This paper adds to the evidence base that 'mitigation pays' with respect to landslide risk in the most vulnerable communities – thus strengthening the argument for ex-ante measures. This integrated project evaluation methodology should be suitable for adoption as part of the community-based landslide mitigation project cycle, and it is hoped that this resource, and the results of this study, will stimulate further such programmes.

Keywords: Landslide modelling, Risk assessment, Cost Benefit Analysis, Developing countries, Community

JEL Classification: D61, Q54, Q58

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1 Demonstrating that mitigation pays

It is widely recognised that the growing incidence and impact of 'natural' disasters is disproportionately affecting developing countries. Numerous studies have documented evidence of the human, economic and environmental losses that developing countries have experienced at local and national levels (for example Charveriat, 2000; UNDP, 2004; Rasmussen, 2004), whilst observing that "the development choices of individuals, communities and nations can generate new disaster risk" (UNDP, 2004, p1). Disaster Risk Management (DRM) and Disaster Risk Reduction (DRR) are now an established part of the extensive development literature, and are increasingly being mainstreamed in policy, often in conjunction with climate change adaption and poverty reduction programmes. However, when it comes to disaster-related expenditure, 90% of bilateral and multilateral funding is still spent on relief and recovery *after the event* (Mechler et al., 2008) despite the acknowledgement that *ex-ante* risk reduction is likely to be preferable from both a humanitarian and economic perspective (Blaikie et al., 1994). Often-quoted statements regarding the macro-economic benefits of DRR include estimates by the United States Geological Survey that if US$ 40billion had been spent globally on preventative measures in the 1990s then disaster-related economic losses could have been reduced by US$ 280billion (IFRC, 2002). However, Benson and Twigg (2004) note that there is "surprisingly little evidence in support of many broad-brush statements" (p13), so that while they may raise awareness of the issue, they provide little concrete evidence upon which decision-makers can justify investments in DRR. Nor do they provide much guidance in deciding which of the many possible DRR projects to invest in.

Studies that have been undertaken with respect to specific disaster risk management projects have also consistently found that mitigation pays – in general, for every dollar invested, between two and four dollars are returned in terms of avoided or reduced disaster impacts (Mechler 2005; Moench et al., 2007). Yet such data on the net benefits of specific DRR approaches are relatively scarce and therefore investment in DRR remains low in the face of numerous competing development opportunities (Benson and Twigg, 2004). A particular challenge in assessing the direct benefits of DRR lies in the fact that they accrue in the future as avoided costs rather than as a continual flow of positive benefits: "the benefits are not tangible; they are…disasters that did not happen. So we should not be surprised that preventive policies receive support that is more often rhetorical than substantive" (Annan, 1999).

In order to build a culture of prevention and enable decision-makers to justify expenditure on disaster risk management and to help decision makers decide which projects to fund, at least two elements are required as a foundation:

- To strengthen the evidence base, the benefits of previous projects need to be substantiated
- The further development of systematic methods for evaluating the effectiveness of mitigation as part of individual project cycles (Benson and Twigg, 2004).

This paper summarizes an ex-post evaluation of a small-scale, community-based landslide hazard mitigation project that addresses both of these elements. The substantive contribution of the paper is in demonstrating that the benefits of the project outweighed the costs by a ratio of 2.7 to 1, adding to the evidence base on the potential effectiveness of DRR projects. In addition to considering the direct benefits from landslide risk reduction, we use a survey-based approach to capture the indirect benefits that accrue to the community, such as improved water supply and access to and from the community. The paper also makes a methodological contribution in developing a new integrated method for the evaluation of landslide hazard mitigation, combining risk assessment and cost-benefit analysis.

1.1 The tools for measuring mitigation

In their comprehensive review of the state-of-the-art in 'measuring mitigation' Benson and Twigg (2004) observe that many of the tools required for analysing effectiveness are already available – specifically, risk assessment methods and economic appraisal methods, such as cost-benefit analysis.

Risk assessment is concerned with identifying and estimating the scale of a specific risk so that it can be evaluated in the light of other risks and risk management options selected. In this context the risk at a certain location is defined as the product of the likelihood of a hazard of a specific type and magnitude occurring, and the vulnerability (degree of damage) of the elements exposed to that hazard. Risk assessment outputs may be qualitative or quantitative (probabilistic) depending on data availability, and the spatial scale and purpose of the assessment. Potential risk management options include: acceptance of the risk, avoidance of the hazard, construction of physical measures to reduce the likelihood of the hazard or its impact, reducing the vulnerability of the elements at risk (through retro-fitting of structures, preparedness or emergency warning, for example), or transferring the cost of the damage via insurance.

Cost Benefit Analysis provides a framework for assessing and quantifying the costs and benefits associated with different projects – either at the project appraisal stage, or as an ex-post assessment. For DRR projects, the benefits are the avoided disaster consequences; quantification requires specifying the probability of the hazard occurring (with and without the disaster risk reduction measures) and the consequences of the disaster. Since many of the benefits occur in the future, the appropriate project lifetime and discount rate also need to be specified. From a policy perspective, the relevant costs and benefits should include welfare consequences and not just the financial benefits, although Moench et al. (2007) note that these wider social elements are often downplayed in practice.

However, while the tools exist, they are rarely implemented in conjunction with each other in the developing world. There are a number of challenges in developing an integrated approach to evaluating effectiveness, including the need for an interdisciplinary approach required, the need for the appropriate tools and data and the general lack of explicit guidelines on how to carry out the analysis in practice. While development organisations have produced numerous manuals on the economic analysis of projects, often emphasising the need to account for disaster risk, they include little guidance on how to actually carry out an analysis of these risks (Benson et al., 2007).

Landslide mitigation in developing countries

Landslide risk in the humid tropics is a good example of the range of issues related to development, disaster risk assessment and mitigation. Rainfall-triggered landslides represent a significant but under-reported threat to lives, property and development in South East Asia and the Latin American and Caribbean region in particular (UN, 2006). The full impact of landslides is masked by broader statistics relating to the precipitation events that trigger them and the associated floods and storm-surges "…even though the losses from landslides may exceed all other losses from the overall disaster" (USGS, 2003, p7). The often numerous landslides associated with each rainfall event occur as individual and discrete small to medium sized events (AGS, 2000) – a scale which is not recognised in most records of natural disasters (such as the EM-DAT database maintained by the World Health Organisation). Spatial scale is also an issue when it comes to landslide risk assessment since the highly localised landslide process controls cannot be adequately represented within the wide-area mapping approaches typically adopted under national DRM programmes. This mismatch of scales is a major reason for the minimal uptake and application of hazard and risk maps in developing countries observed by Opadeyi et al. (2005) and Zaitchik et al. (2003).

In cases where detailed spatial and temporal data *are* available at the appropriate scale for landslide risk assessment it is possible to identify mitigation strategies and to demonstrate their effectiveness using some form of economic appraisal. Examples of the application of integrated landslide management approaches can be found in Hong Kong (Wong et al., 1997; Dai et al., 2002), the USA (National Research Council., 2004), and Europe (Blöchl and Braun, 2005) – all of which are in the developed world, are 'data-rich', and have the capacity for designing and applying such analytical tools. Analogous approaches may also be found with respect to other hazards such as avalanches (Switzerland: Brundl et al, 2009) and floods (UK: Penning-Rowsell et al., 2005). However, in the developing world "the knowledge-base required to identify landslide-prone areas is often nonexistent or fragmentary" (UN, 2006) and the practical implementation of risk reduction on the ground is limited, even when money is available (Wamsler, 2006). Amongst the handful of specific DRR cost benefit studies identified by Moench et al. (2007) the majority are related to hurricane and flood risk management, and almost half are from the USA.

Referring to the two research needs identified earlier: i) there is little concrete evidence of the benefits of landslide risk reduction in developing countries, despite the impact that these hazards are having; ii) with respect to the need for integrated project evaluation methods, Dai et al. (2002) note that "in order to mitigate landslide hazard effectively, new methodologies are required to develop a better understanding of landslide hazard and make rational decisions on the allocation of funds".

A prototype assessment of community-based landslide mitigation measures

In this study we bring together quantitative landslide risk assessment and cost benefit analysis in order to undertake the ex-post evaluation of a community-based landslide risk reduction intervention in Saint Lucia. The aim was to start to build the evidence-base that landslide mitigation can pay, and to develop a prototype integrated methodology. The landslide risk reduction approach used in this study is the MoSSaiC approach (Management of Slope Stability in Communities) which has been developed and applied in the Eastern Caribbean (Anderson et al. 2008, 2009; Holcombe and Anderson, 2009, 2010,). It is designed to identify the causes of slope instability and the vulnerability of the elements at risk at the scale of individual hillsides and communities, thus determining appropriate landslide hazard reduction measures which are then constructed by the community. In this case the interaction between surface water infiltration and anthropogenic influences on slope hydrology were found to be the dominant mechanisms in determining the stability of the slope. This is a typical scenario for rapidly urbanising, unplanned communities in developing countries. The primary risk management strategy was therefore to design and build surface water drains and connect households to this new drainage network. Using this MoSSaiC intervention as an example we demonstrate the application of cost benefit analysis and provide an estimate of the direct and indirect economic benefits of the landslide mitigation project. Key elements of the analysis described here include the numerical modelling of the slope in order to determine the probability of a landslide occurring before and after the intervention; the assessment of vulnerability and the direct costs of a landslide; the design and application of a survey-based assessment of indirect project benefits to the community; and the estimation of the project benefit-cost ratio. In accord with Benson and Twigg (2004) each of the methods used in this study is 'standard' in its own field, but they have rarely been applied in an integrated fashion or in the context described here.

1.2 The study area: a typical unplanned community in the Caribbean

With respect to rainfall-triggered landslide risk, the Caribbean region is typical of many developing countries in the humid tropics. The steep slopes and deep soils which characterise much of this region are naturally prone to landslides which are triggered by high-intensity or high-duration rainfall (Lumb, 1975). A combination of poverty and increasing levels of urbanisation is resulting in the construction of informal settlements on such slopes as they are often the only available location for the poor (Board on Natural Disasters, 1999). In common with many other developing countries, urban areas in Latin America and the Caribbean suffer from low-quality housing, inadequate (or unenforced) urban planning controls, and insufficient investment in infrastructure (Charveriat, 2000). The landslide risk that results is the product of complex interactions between the inherent susceptibility of slopes to landslides (related to their soils and geology, topography, hydrology and vegetation); the influence of human activities in affecting these factors at a highly localised scale; and the vulnerability communities to the impact of landslides. Figure 1 shows typical hillside communities in Castries, Saint Lucia, consisting of wooden or concrete-block housing constructed on concrete piles or cut and fill terraces.

Fig. 1 near here

Landslide hazard and vulnerability are not often quantified in this setting since, as noted previously, landslides tend to occur as relatively small discrete events in contrast to other natural hazards (Bull-Kamanga et al., 2003). The various hazard-mapping initiatives which have been undertaken in the Caribbean have utilised the basic wide-area digital data available (relating to topography, geology, and land use for instance) to estimate zones of landslide susceptibility (Caribbean Development Bank, 2004). However, the *scale* of the mapping in relation to the scale of the triggering mechanisms limits the application of such maps for designing site-specific mitigation measures in communities. Zaichik *et al.* (2003, p267) note that such “management-oriented hazard models have been applied in the developing world only rarely and with mixed success… in large part because of the limitations of relevant historical and biophysical data”.

In contrast to more top-down approaches the MoSSaiC methodology has been developed at the scale of the communities and hillsides, thus accessing community information and slope parameters at a process-relevant scale. This enables engagement with residents and government experts (such as engineers, surveyors, planners and community development officers) in order to develop a comprehensive assessment of the likely landslide triggers, the level of the hazard and the potential impact. Typically, the dominant instability mechanism in these densely constructed communities is the infiltration of rainfall and household water into the slope material and the concentration of such flows at landslide-prone locations due to altered surface water runoff and slope drainage patterns. Landslide hazard mitigation measures therefore consist of appropriately located drains to intercept and control surface water, the capture of roof-water and the connection of households to the drainage network.

This study evaluates the implementation of a MoSSaiC project in 2008 in a typical unplanned community in Castries, Saint Lucia. The community consists of 20 households located on the lower slopes of a moderately steep (30 degree) ridge between a road along the mid-contour of the slope, and the ravine at its base. Although this ridge is densely populated, several contiguous communities, of between 20 and 80 households each, can be distinguished on the basis of topography, the location of ravines which incise the slope, land registry parcels (within which the plots are rented and developed in an uncontrolled manner), and a recognised community identity or local name. The plan of the study site in figure 2 indicates the topography, the location of houses in one such community and their form of construction, and the alignment of the new drains.

Fig. 2 near here

The convergent topography of the community means that the flow of surface and sub-surface water is concentrated at certain locations. This drainage pattern coincides with the deep residual soils and has resulted in minor landslides triggered by heavy or prolonged rainfall events. The vulnerability of the community to events such as landslides is also typical of unplanned settlements in the region in terms of poor construction standards, limited access, lack of drainage, and poverty levels. The 2001 census data for the enumeration district of 96 households indicates a Core Welfare Index of 10.72 (where the maximum score is 20). This is an aggregate measure developed by the Government of Saint Lucia (GoSL, 2004) which characterises household welfare based on the house construction material, level of sanitation, electricity, possessions, overcrowding, education and employment. Typical scores for enumeration districts relating to communities on the slopes surrounding Castries (the main urban area) range from 8 to 11.5, while the poorest individual households can have scores as low as 7. This indicates houses with wooden walls, no flush toilet and 2-3 persons sleeping in one room. The household head has only primary level education, and there is only one employed person for every 2-4 dependents.

Measuring landslide mitigation at the appropriate scale

The main methodological challenges to developing the necessary evidence-base and integrated approach for evaluating landslide mitigation are related to data availability, scale, process-representation and the cross-disciplinary interface between the different components of the analysis. Additional challenges may come from the development policy and funding contexts– where constraints such as local capacity, project funding cycles, top-down approaches and the need for measurable project outputs do not always directly relate to the 'science' of the risk assessment and mitigation measures.

By basing this study on a recently-completed landslide risk reduction intervention at the scale of a single community, it is possible to overcome many of these potential problems. In this context the landslide hazard can be quantified (using physically-based modelling methods) and it is possible to make a direct assessment of the vulnerability and of the benefits of landside mitigation. Additionally, knowledge of, and access to, the local community through the project means that is also possible to make an estimate of the direct benefits from the risk reduction, as well as some indirect benefits that accrue to the community (such as improvements in water supply and access to and from the community).

The structure of this paper reflects the development and application of this methodology with respect to the study site in Saint Lucia. Section 2 describes quantification of the landslide risk in terms of the hazard and exposure and vulnerability of elements at risk. Landslide hazard (frequency and magnitude) is modelled with and without the drainage intervention. These hazard predictions are then used to estimate the damage potential of the elements exposed. Based on this, section 3 estimates the monetary value associated with the intervention. Damage costs are assigned to different landslide scenarios; the benefits of intervention are then defined as avoided landslide costs. Additional project benefits to the community are estimated using a survey approach. The overall cost benefit analysis takes into account the present values of project costs, estimated direct benefits (avoided costs of a landslide), and estimated indirect benefits. The ratio of benefits to costs for different investment scenarios (no risk reduction intervention, versus intervention and maintenance, versus intervention and no maintenance) gives an indication of the effectiveness of the project. Finally, a sensitivity analysis is undertaken with respect to key parameter values (such as the discount rate) in order to indicate the robustness of the result. This integrated approach is presented in figure 3 in terms of data inputs, analytical methods and models, and quantified risk outputs.

Fig. 3 near here

2 Modelling the reduction in landslide risk

Landslide risk can be defined as the product of the probability of the occurrence of a landslide hazard, and the consequences of that event. These consequences are determined by the spatial impact of the landslide with respect to the elements at risk and the vulnerability of those elements to damage (specifically houses in this study). To assess the effectiveness of a landslide risk reduction project requires an evaluation of each of the terms in this risk equation before and after the intervention. In this section we briefly review the available methods for such an analysis. A deterministic slope stability model is applied in order to quantify landslide hazard frequency and location, and an empirical approach is taken to estimate the depth and travel distance of landslide debris. This allows the exposure and damage potential (vulnerability) of houses in the community to be assessed on the basis of predicted landslide location and extent. The next step, in section 3, is to assign values to the elements at risk and undertake a cost-benefit analysis to establish if there is any significant change in landslide risk due the drainage intervention.

2.1 Landslide risk assessment: conceptual framework

Landslide hazard assessment methods

The specific outputs required from the hazard assessment are as follows (after Wong et al., 1997):

- probability, or frequency, of the specific landslide event
- location and depth of the slip surface
- travel distance of the failed material from the landslide source area
- damage corridor width
- depth of deposition
- velocity of travel within the damage corridor.

Landslide hazard assessment methods fall into four different classes: i) inventory-based (probabilistic) and empirical; ii) heuristic (expert) assessment of landslide susceptibility; iii) statistical (bivariate or multivariate) modelling of slope parameters; iv) deterministic modelling of the slope processes (Dai et al., 2002). Selection of the most appropriate approach for a given study must consider the specific aspects of landslide hazard the approach is designed to assess, the spatial scale for which it is most appropriate, the data requirements, and the level of quantification it affords (van Westen et al., 2006; van Westen et al., 2008). Against these criteria a deterministic approach was taken in the assessment of landslide frequency and location, and empirical equations were used to calculate landslide runout distance and depth. Landslide velocity was assumed on the basis of expert judgement relating to landslide hazard frequency and location. The rationale for this research design, and the details of the different model components are discussed below.

Deterministic approaches are designed to model specific slope processes on the basis of the physical properties of the slope, with data requirements and quantitative outputs depending on model complexity and the physical processes represented. They are most appropriately applied to specific slopes where physical parameters can be acquired at a suitable scale, rather than over wide areas with less well known properties. The model used in this study was CHASM, a physically-based dynamic slope hydrology and stability model with data requirements which are compatible with the typical data available in developing countries. A full description of the model can be found in Anderson et al. (1996) and Wilkinson et al. (1998, 2000). Examples of previous CHASM applications in similar urban communities in the Caribbean can be found in Anderson et al. (2008) and Holcombe and Anderson (2009); and in Karnawati et al. (2005) in the context of rural community-based projects in Indonesia. Here, the main components of CHASM are outlined with respect to the assessment of landslide frequency and location.

For a specific slope cross-section CHASM models the dynamic influence of external forcing variables (landslide triggering factors), specifically rainfall and slope hydrology, on the slope factor of safety over time. The slope cross-section is represented by a regular mesh of columns and cells, the centres of which are computational points for a forward explicit finite difference scheme which solves equations for water fluxes within the slope. The one dimensional form of the Richards' equation is solved in order to determine vertical infiltration in the unsaturated zone, with the Millington-Quirk procedure defining the unsaturated hydraulic conductivity of the slope material from the specified suction-moisture curve. When the water table is reached the explicit solution of the Darcy equation for saturated flow is used to calculate lateral flow between columns in two dimensions. The hydrological component of CHASM can therefore simulate the infiltration of rainfall, changes in the saturated and unsaturated zones, and the development of perched water tables over time. The resulting dynamic pore pressure field (both positive and negative pressures) is incorporated directly into the Mohr-Coulomb equation in order to determine the effective soil shear strength. CHASM uses Bishop's (1955) simplified circular method for estimation of the slope factor of safety (F) – the ratio of the shear strength of the slope to the shear stresses acting upon it. An automated search procedure identifies the slip surface with the minimum F at any given time-step (Wilkinson et al., 2000). As the hydrology changes over time the slope factor of safety and the location of the critical slip surface will also vary. If F falls below 1 this indicates slope instability and the occurrence of a landslide.

The input parameters required by CHASM are: slope geometry at the selected cross-section, the location and depth of different slope material strata, geotechnical and hydrological parameters for each strata (cohesion, angle of internal friction, bulk density, saturated moisture content, saturated hydraulic conductivity and suction-moisture curve), and the location of the initial water table. Boundary conditions – water fluxes – should be specified for the left-hand (upslope) and right-hand (downslope) columns (it should be noted that CHASM cannot simulate seepage at the slope face, and the water table must pass through the right hand boundary). The base of the mesh is a no-flow boundary, whilst the rainfall is imposed on the top boundary at user-defined times and intensities. Slope plan curvature (convergence and divergence) can be accommodated in the model by varying the breadth of the columns (Anderson et al 2008). Where such data is available CHASM can also simulate the effects of vegetation (Wilkinson et al., 1998), point-water sources and loading (Anderson et al., 2008) on the slope.

CHASM can be used to predict the probability of a landslide occurring (if the frequency, or return period, of the simulated rainfall is known) and the spatial extent of the landslide within the slope in terms of the slip surface location (assumed to be circular, as is appropriate for rotational landslides in deep soils) and the volume of the failed material. At a specific site assumptions can be made as to the lateral extent of the landslide across the slope on the basis of any constraining topography (such as concave geometries, i.e. convergence zones) and material properties (such as bedrock outcrops). This allows the exposure and vulnerability of elements with the landslide mass to be assessed. However, CHASM (in common with all dynamic limit equilibrium models) is not designed to account for the runout behaviour of landslides and therefore cannot be used to predict the exposure or damage to elements in the path of the debris. To quantify this aspect of landslide hazard requires either the application of a numerical model which specifically incorporates runout behaviour or the use of empirical methods based on records of previous landslide events (such as those developed by Corominas, 1996; Wong and Ho, 1996; and Finlay et al., 1999).

Landslide runout can be modelled deterministically using lumped mass energy models such as the basic friction or 'sled' model proposed by Sassa (1998; in Vaunat and Leroueil, 2002). Other deterministic models deal with both the slope failure and the resulting runout: for example, analysis of continua – the stress-strain deformation of slope material (e.g. FLAC, from Itasca, 2000); and sophisticated models which simulate discontinuous and multi-phase materials, or grain-scale mechanics (such the Discrete Element Model by Cundall, 2001) which can simulate both the spatial extent of displacement and also the velocity. In this study the application of the lumped mass approach (the least complex model) was not considered appropriate due to its assumption of a fully-drained slip surface. While FLAC has previously been applied in a back-analysis of a landslide in a similar community (Anderson et al., 2008); such numerical methods are generally highly data intensive and require significant modelling expertise in order to deliver reliable outputs.

Empirical runout methods require few measurable parameters and, if the landslide type is properly identified and the relevant equations used, Wong and Ho (1996, p419) assert that such an approach provides a "quick and realistic assessment of the likely range" of runout distances and depths. In this study the an empirical approach was adopted, using equations derived by Finely et al. (1999) from a database of cut slope failure measurements in Hong Kong (where the rainfall, soil characteristics and landslide mechanisms are comparable with those in the Caribbean). These equations require three parameters which can be readily obtained from CHASM simulations, namely initial slope angle, the depth of the slip surface and the height of the landslide crest above the base of the slope.

Exposure and vulnerability assessment methods

Having identified the probability of a landslide hazard of a given type and magnitude the next stage in the risk analysis framework is to determine the exposure and vulnerability of different elements (people, property and infrastructure) to that hazard. The exposure of an element describes its location with respect to the landslide – whether it is on the upper or side margins of the slide, within the failed mass, or in the path of the debris; and for people, whether they are in the open or in a building or vehicle (Zêzere et al., 2007). The vulnerability of these elements is expressed in terms of the potential degree of damage (or loss) on a scale of 0 to 1 with respect to the magnitude (or intensity) of that landslide. Losses can be translated into monetary terms on the basis of the value of property, or into Potential Loss of Life (PLL) for people. In some analyses a 'Value of Life' assumption is also made (Wong et al., 1997; Kong, 2002; Bründl et al., 2009), however assigning such values can be controversial and they are generally utilised in wide-area studies where multiple hazards and risk reduction projects are being compared. To determine the exposure and vulnerability of people to given landslide requires both spatial and temporal relationships to be considered – where they are at the time of the slide and whether they are protected by structures, or whether they can escape the landslide given its velocity. Due to the complexity of quantifying these relationships and assigning PLL or value of life terms, the impact of landslides at the study site focuses on the exposure and vulnerability of property.

Vulnerability is difficult to quantify since elements do not have an intrinsic vulnerability (Zêzere et al., 2007), there is no unified method for assessing vulnerability of property with respect to its exposure to different landslide hazards (Glade and Crozier, 2005), and there is a scarcity of information about different landslide types, volumes and elements at risk (van Westen et al., 2008). Where comprehensive landslide databases do exist an empirical approach can be taken to both the estimation of damage potential and the translation of this into absolute cost. The best examples of this approach can be found in the developed world, for example in Hong Kong (Wong et al., 1997), which is almost unique in maintaining detailed records of all landslides and their consequences (Dai et al., 2002). Such studies allow the development of empirically-based damage matrices which relate vulnerability to building characteristics, exposure and various measures of landslide intensity (Zêzere et al., 2007). In the absence of such a complete dataset other countries have taken a 'pragmatic approach' to risk analysis (Bründl et al., 2009), incorporating subjective and qualitative vulnerability information from experts and local practitioners. In many cases the basis for the derivation of vulnerability values is not explicitly stated (Glade and Crozier, 2005).

A typical wide-area vulnerability analysis is that of the InterRisk Assess project in the Swabian Alb, Germany, which established five levels of landslide damage to buildings ranging from "slight non-structural damage, stability not affected, furnishing or fittings damaged" with a vulnerability of 0.01-0.1, to "partly or totally destroyed, evacuation necessary, complete reconstruction: 0.9-1" (Blöchl and Braun, 2005, p393). With respect to a landslide susceptibility map, the vulnerability of each exposed building was assessed, with the greatest weighting being placed on construction material (Papathoma-Köhle et al., 2007). For small-area studies in which the probable landslide location, slip surface geometry and runout characteristics have been identified it is possible to be more specific about the damage to each element since both the landslide intensity and building resistance are known in greater detail. Li et al. (2010) proposed damage potential equations based on the dynamic intensity (velocity) of the landslide, and the geometric intensity – in terms of deformation within the body of the slide and deposition depth below the slide. The resistance of different building structures to these forces was systematically defined according to expert judgement on the basis of construction material, foundation depth relative to slip surface depth, maintenance standard, and number of storeys.

In this study the prediction of landslide slip surface locations, volumes and runout distances allowed the assessment of the exposure of each house. The following four scenarios were envisaged:

- Undercutting of <20% of house at the landslide margins (crest and side-scarps) or within the landslide body, where the slip surface is deeper than the foundations, leading to minor structural damage (0.5) but not loss of possessions
- Undercutting of 20-100% of house at the landslide margins (crest and side-scarps) or within the landslide body where the slip surface is deeper than the foundations, leading to structural damage (1) but not loss of possessions
- Deposition of runout material at a depth less than half the height of the house leading to minor structural damage (0.5) and loss of possessions due to flooding of property
- Deposition of runout material at a depth greater than half the height of the house leading to structural damage (1) and loss of possessions due to collapse of the building and/or flooding

Although the building material for each house was known, this was not accounted for in determining the resistance of the property to the predicted landslide, only in assigning the direct costs of rebuilding.

2.2 Results of landslide risk assessment: two scenarios

Landslide hazard: frequency and magnitude

Several minor landslides were already in evidence at the study site before the drainage intervention was undertaken. These minor slope failures all occurred at locations where the slope geometry had been altered in the course of house construction. In each case the cut slopes failed during periods of prolonged or heavy rainfall, sometimes overturning poorly-built retaining structures or threatening the houses immediately above and below. Such small-scale, shallow slides are a common occurrence in densely constructed unplanned communities. However, more extensive landslides can be triggered under certain conditions, affecting whole hillsides and requiring the rebuilding or relocating of communities. Locations which are particularly susceptible to these mid- to large- scale landslides often exhibit convergent topography and drainage patterns and the accumulation of deep residual soils. The site in this study has such characteristics in that it lies on the lower slopes of steep ridge which is incised with minor drainage channels. One such drainage route passes through the study site in a natural hollow which is flanked by bedrock outcrops. Deep soils have accumulated in the hollow and seepage can be observed in the lower slopes even during dry periods.

To capture the drainage and slope processes occurring along the cross-section of this topographic convergence zone, and to reflect the two possible landslide scenarios, CHASM was used to model the stability of the study slope at two scales:

- Scenario A: whole slope failure. A 132m cross-section was defined from the road at the top of the community to the ravine at its base (an elevation change of 65m), and which captured the original 30-35° slope topography as depicted by the official government topographic survey.
- Scenario B: cut slope failure. Within the 132m cross-section a 53m sub-section was identified which incorporated the detailed surface topography which typifies such communities. Specifically, this section included two 60° cuts in the residual soil and the associated benches (terraces) on which houses have been constructed.

The cross-sections identified for modelling these two scenarios in CHASM are illustrated in figures 5 and 6 (at the end of this section). These slope cross-sections were discretised into columns and cells of 1 metre square. The specification of slope material strata was based on reports by residents who had carried out excavations for the construction of their house foundations – this evidence also indicated that the surface strata was likely to be at residual strength due to historic disturbance, landslides and accumulation of colluvium. The geotechnical and hydrological properties of the slope materials are typical of those found in the slopes of the Castries basin in Saint Lucia. In particular, the cohesion and angle of internal friction of the surface strata (a completely weathered soil) were specified as 4 and 25° respectively, based on previous shear box tests of similar soils from the area and assuming that this material is at its residual strength. The values of the key soil parameters for the different strata are given in table 1.

Place **Table 1** near here

From field evidence of water table depth observed from house piling (upslope) and from local seepage zones (downslope) the water table was assumed to be at a depth of 15m at the left-hand boundary, with no flow through this boundary (i.e. no upslope recharge); at the right hand boundary the water table was set at less than a metre below the surface, with flow out of the domain permitted through all cells in this final column. Each CHASM simulation was initiated with these conditions and run for 168 hours to allow steady-state hydrology to be established. A time-step of 1 second was used for solving the hydrological equations routing water through the slope, while the slip surface search and slope stability calculations were undertaken hourly.

Starting at hour 168 a 24-hour rainfall event was simulated by imposing water on the top boundary of the slope at a specified intensity. After the rainfall event the simulation was run for a further 168 hours to allow the movement of infiltrated water through the strata. Six separate 360-hour simulations were run for each slope cross-section with increasing intensity and decreasing probability of occurrence. In this way the slopes were tested for stability against the 1:1.5, 1:5, 1:10, 1:20, 1:50 and 1:100 year 24-hour storms. These design storms were derived from rainfall Intensity Duration Frequency (IDF) relationships developed for Saint Lucia (Klohn-Crippen, 1995) and are comparable to rainfall characteristics defined for other countries in the region such as Puerto Rico and the US Virgin Islands (Bonnin et al., 2006).

Under scenario A it was found that the rainfall events of the magnitude of the 1:10 year storm and above triggered a landslide in the lower section of the slope at hour 273. The slip surface was predicted to coincide with the interface between the residual soil and the weathered bedrock. The timing of the landslides after the end of the rainfall event was related to the continued water table rise at the base of the slope as soil water flowed through the soil profile. The post-failure geometry of the slope was found to be inherently unstable and a subsequent landslide was predicted upslope of the first. This progressive migration of landslides up a slope is to be expected due to the over-steepening of the slope at the crest of each slide. In the simulations for scenario B the slope demonstrated a greater response to rainfall with shallow cut slope failure predicted immediately after the 1:5 year storm at hour 195. The response of the hydrology and stability in this cross-section reflects the effect of the localised steepening of the slope (the 'cut') and is in accord with the observation that a number of this type of minor slope failures are known occur every year in St Lucia. In the study site there are at least three locations with a similar geometry to the one modelled. Figure 4 depicts the typical location of housing on such slopes – in this instance the cut slope above the house has failed causing damage to the walls and foundations and necessitating the rebuilding of the structure.

Fig. 4 near here

Elements at risk: exposure and damage potential

For each of the two scenarios simulated using CHASM the exposure and vulnerability of houses within the failed mass could be directly determined on the basis of the location of the predicted slip surface. However, the identification of houses exposed to the *debris* involved the estimation of the landslide runout distance and depth of the debris. Empirical runout relationships derived by Finlay et al. (1999) were used for this calculation on the basis of the comparable landslide type, scale and material properties to those landslides from which the equations were originally derived. With respect to landslide type, previous failures in the community were shallow rotational slides with no evidence of liquefaction. The input parameters for these calculations were derived from CHASM; these were the initial slope angle, the depth of the slip surface and the height of the landslide crest above the base of the slope. For scenario A the total runout distance, with respect to the crest of the second (upper) landslide, was predicted to be between 31 and 47m from the crest of the failure in the horizontal direction (using the Finlay et al. equations for the 5^{th} and 95^{th} percentiles). This equates to a maximum travel distance of 10m from the toe of the slip surface – a maximum horizontal displacement of the failed material of 125% with respect to the original source area. The depth of the debris accumulated at the base of the slope was estimated to be between 2.5 and 5m. The travel distance of the scenario B landslides was calculated to be between 1 and 5m from the toe of the slope (a maximum of 177% displacement with respect to the source area) – this was relatively high compared to the larger scenario A landslide due to the steeper slope angle (50° for cut slopes, compared to 28° in scenario A). The predicted depth of the debris at the base of the failed cut slopes was between 1.7 and 3.3m. Finally, the width of the landslides was estimated on the basis of constraining geology and topography (for scenario A). For scenario B, confinement is not attributable to confining topography – rather the landslide width was estimated by reference to the width of previous cut slope failure geometry.

Figures 5 and 6 illustrate the predicted landslide locations, magnitude and the estimated damage of the exposed houses based on the four damage scenarios identified at the end of section 2.1. Houses are identified on these plans which are predicted to be lost (i.e. damage potential = 1) or damaged (0.5), or where possessions are lost. This is based on their location with respect to the failed area, debris and slip surface depth. Table 2 summarises the number and type of house in each of these damage categories.

Fig. 5 near here

Fig. 6 near here

Table 2 near here

2.3 Effect of intervention in reducing landslide frequency

Where the infiltration of surface water into a slope is a dominant process in triggering landslides it is possible to improve slope stability by removing some of this water through the interception and drainage. The two main components of MoSSaiC interventions are thus the construction of a network of surface drains to intercept surface water runoff and convey it to main drains or natural water courses, and the connection of household roof water (using roof guttering to capture rainfall) and grey water to these drains (Anderson et al., 2008). There are three possible sources of surface water to be addressed in unplanned communities:

1. Rainfall intercepted by roofs – captured by roof-guttering and conveyed to drains.
2. Rainfall falling directly onto the slope, a proportion of which will generate surface runoff and which can be intercepted by contour drains.
3. Mains water supplied to households and discharged onto the slope as grey water (bathroom and kitchen waste which can be connected to the drains) and black water (septic waste which cannot be dealt with by surface drains).

The effectiveness of surface drains and household connections in reducing landslide frequency can be assessed by calculating the amount of water intercepted before it can infiltrate into the slope. In this study the amount of rainfall intercepted by the roofs of the houses is known to be 35%. This is based on the estimation of the areal extent of the community from the aerial photos and topography map, and the calculation of the roof area of each house (using measurements from the survey undertaken for the installation of the guttering). It is therefore assumed that the installation of the roof guttering and its connection to the drains will reduce the total volume of rainfall reaching the slope surface by 35%. This translates to a 35% reduction in the 'effective intensity' of the design rainfall events used in the CHASM slope stability simulations. Since rainfall IDF (intensity, duration frequency) relationships are non-linear the predicted probability of landslides occurring in a given year is reduced by an order of magnitude – from 0.1 to 0.01 for scenario A, and from 0.2 to 0.02 for scenario B. Table 3 compares these rainfall intensities before and after the installation of the guttering and shows the subsequent improvement in the slope stability simulated by CHASM.

Table 3 near here

The estimate of a 35% reduction in effective rainfall is conservative in that it only represents rainfall intercepted on the roofs of houses, captured by the new guttering and directed into the drains or water tanks. In reality the drains intercept surface water runoff which would otherwise be concentrated at convergence zones and infiltrate into the soil. It would be realistic on the basis of experience in the field to estimate that perhaps 50% of surface runoff would be intercepted in this manner. However, to robustly quantify of the volume of surface water runoff and its capture by the drains would require additional data for the characterisation of slope hydrology and drain flow rates. Similarly, the effect of connecting household grey-water to the drains is ignored due to uncertainty in household water consumption and leakage of mains-water pipes. Thus, the CHASM simulation results in table 3 represent a conservative of the improvement in slope stability with the intervention. An even greater reduction in landslide probability would be expected were the effects of surface water and grey-water interception to be included.

Figures 7 (Scenario A) and 8 (Scenario B) show the changing stability (Factor of safety, F) in response to the three levels of effective rainfall (no intervention, 35% and 50% reduction) as modelled by CHASM for each of the slope cross-sections. As described in section 2.2, values of F initially rise due to the drainage of the initial water table through the slope profile. At hour 168 the critical 24-hour design storm starts (the 1:10 year storm in scenario A, and 1:5 for scenario B) and F drops as water infiltrates and reduces the shear strength of the slope material. It can be seen that the reduction in F is greatest and most rapid where there is no drainage intervention to remove the surface water. In both slopes F drops to 1.01 which, in this study, and in a conservative slope design context, is interpreted as slope failure. As would be expected, in the case of the larger slope (scenario A, figure 7) the hydrological and slope stability response is much slower due to the greater flow routes involved. The minor oscillations in F in scenario A correspond to the identification of different minimum-F slip surfaces by CHASM from one time-step to the next. With the conservative calculation of a 35% reduction in effective rainfall both slopes are predicted to remain stable; while the 50% reduction (which includes the likely surface water interception) results in a further improvement in stability.

Fig. 7 near here

Fig. 8 near here

3 Expressing risk reduction in monetary terms: estimating project costs and benefits

The estimates of the landslide hazard and the resulting exposure and damage to homes are central to estimating the benefits of the intervention as part of a wider cost-benefit analysis. This is the aim of this section. Economic appraisal of risk reduction projects was identified at the start as a vital means of strengthening the evidence base for investment in disaster mitigation. This section provides estimated monetary values for both the costs and (direct and indirect) benefits which would allow policy makers to assess the overall effectiveness of the project in terms of single metrics such as Net Present Value (which expresses the present value of total benefits minus the present value of total costs in monetary terms) or the Benefit-cost ratio (which expresses the present value of total benefits relative to the present value of total costs).

Before going into detail on how individual cost and benefit elements were estimated, Table 4 summarises our central estimates of the total costs and benefits of the project. The costs are mainly those incurred in 2008 when drain construction and guttering installation were undertaken, minor additional costs accrue where ongoing maintenance is assumed. There are direct benefits from the reduction in landslide risk (which reduces the expected cost of rebuilding damaged homes and replacing lost possessions); there are also indirect benefits arising from improvements in the everyday lives of community residents. Separate estimates are presented for the case where community residents continue to carry out maintenance and the case where they do not.

The figures in table 4 clearly show that the estimated total benefits outweigh the total costs, particularly in the case when there is maintenance. The benefit-cost ratio without maintenance is 1.7, rising to 2.7 if maintenance is carried out. This increase reflects the fact that the cost maintenance is fairly low cost but is assumed to extend the life of the project – and hence the benefits of the project – by thirteen years.

Since most of the costs are upfront while the benefits occur for several years into the future, the estimated net present value is sensitive to the choice of discount rate. The estimates in table 4 assume a real discount rate of 12 per cent, being the upper limit of values typically used by the World Bank (Belli et al., 1997; Gwilliam, 2000). The choice of discount rate will affect the size of the estimated benefit-cost ratio but has much less effect on *whether* the project generates net benefits. Benefits can be shown to exceed costs with a rate as high as 170 percent, far in excess of any reasonable range for the discount rate.

Table 4 also usefully highlights the source and distribution of the benefits of the project. The greatest benefit comes from the reduction in the landslide risk itself and the fact that this reduces the potential costs from having to rebuild houses and replace possessions. Much of this is likely to be a benefit to the government which would otherwise bear the majority of such costs. For example, the 1999/2001 Black Mallet landslide in Saint Lucia required the relocation of approximately 60 households at a cost to government of US$ 8 million in the form of a loan from the Caribbean Development Bank (Anthony, 2001). However, there are also substantial indirect benefits to the residents of the community arising mainly from improvements in access (due to reduced local flooding) and increased rainwater harvesting (thus, reducing water bills). In the rest of this section, we provide more detail on how each of these benefits is estimated.

The costs and benefits have been estimated on a fairly conservative basis – taking the maximum of any possible costs and the minimum of any possible benefits. Also, as shown below, there are also a number of additional benefits to local residents that have not been included in the cost-benefit analysis because of possible uncertainty over which values to use, such as for leisure time. This means that the figures are likely to underestimate the total benefits.

Table 4 near here

3.1 Estimated costs

Estimates of the different components of project costs are shown in table 5. These are based on the standard unit costs of construction adopted by the government social development agency which implemented the project. In total 225 metres of concrete block surface drains were constructed with cross-sectional dimensions of between 0.3 x 0.3m and 0.6 x 0.6m and at an average unit cost of EC$ 350 per metre run. The total cost of materials for drain construction was EC$ 78.750. Each of the 20 households in the community received roof guttering, downpipes (connecting to water tanks in some cases) and grey water connections to the drains at a total cost, for materials, of EC$ 25,580. The drain construction and roof guttering installation were divided into four separate work packages and the contracts were let to local contractors. The construction of two of the drains took 20 days, while the third drain and the roof guttering installation took only 10 days each. The contractors were required to hire labourers from within the community or from neighbouring areas. The social development agency which managed the contracts and supervised the works reported that 23 members of the community and 5 others were employed as labourers at a rate of EC$ 80 per day. A contingency was also added for possible other costs incurred. Although the actual records of expenditure were not made available, the estimated initial project cost of EC$ 150,000 is in accord with other similar MoSSaiC interventions for this size and type of location.

If the drains are kept free of debris and correctly maintained and the household connections are kept in working order, the benefits of the project can be extended for a longer period – 20 to 25 years (versus 7 to 8 years with no maintenance). The required level of drain maintenance is estimated at one hour a week. We calculate the present value of the cost of maintenance carried out over 20 years, assigning an hourly wage rate of EC$ 8.28, the average maximum wage in St Lucia.[1]

Table 5 near here

3.2 Estimating direct benefits from risk reduction

The benefits of a reduction in landslide risk can be quantified by comparing the expected costs from landslides *without* the intervention having occurred, to the expected costs from landslides *with* the intervention having occurred. The hazard assessment component of this study has identified two landslide scenarios and their associated frequency and magnitude, and the expected damage potential of the exposed houses. For each landslide risk scenario the estimation of the direct benefits of the intervention involves the translation of these damage potentials into costs, incorporation of the probability that these cost will be incurred with and without the intervention, and finally the calculation of the net present values of expected costs. This expresses the future costs at today's values using the process of discounting.

Monetising the landslide consequences

The estimated total costs associated with each type of landslide are summarised in table 6. For each house lost, there is a monetary cost in rebuilding the house and in providing temporary accommodation to its tenants. The estimates of rebuilding costs are based on a report on housing prepared for the Government of Saint Lucia (ECMC, 2007); it is estimated that the cost to rebuild a wooden house is EC$ 55,000, and the cost to rebuild a wood/concrete house is EC$ 65,000. We assume that to rebuild any house will take 12 months, and that the annual cost to rent temporary accommodation for its tenants is EC$ 2,460 (based on the cheapest available 2-bedroom public sector rented housing). For damaged houses, we assume a single repair cost of EC$ 10,000 for each damaged house, irrespective of house type; this is half the maximum grant available for house repair from the government. For each house losing possessions, there is a cost in replacing those possessions. Our estimate of this cost is based on the mean estimate of the value of their possessions given by survey participants (see section 3.3): this is EC$ 11,300.

Table 6 near here

Incorporating the landslide probabilities

We made a number of simplifying assumptions regarding landslide probabilities: First – that that once a scenario A landslide has occurred, the landscape is sufficiently altered that from then onwards no landslide of *either* type may occur in *any* location. Secondly – that once a scenario B landslide has occurred in a particular location, it cannot occur in that location again. Finally – that any scenario B landslide preceding a scenario A landslide in the same year may be treated as if it had not occurred. This is due to the difficulty in assessing what proportion of the costs of the smaller scenario B landslide would be made irrelevant by the costs of a scenario A event. These assumptions are designed to avoid double-counting landslide costs and are consistent with providing a conservative estimate of intervention benefits: any relaxation would lead to an increase in costs.

CHASM provides two annual probabilities for each landslide scenario corresponding to the whether the drainage intervention has been implemented or not. Given the assumptions described above, these may be interpreted as follows: for scenario A landslides, they are the probabilities that a

[1] Based on St Lucian government data for 2003, available at http://www.stats.gov.lc/wagavg.htm. This is a firm-level survey which asks employers to report the minimum, average and maximum wage paid to workers of each occupation type. We use the average maximum as an upper bound on wages.

scenario A landslide event will occur in a given year, given that a scenario A event has not occurred before. For scenario B landslides, they are the probabilities that a scenario B event will occur in a given location in a given year, given that a scenario B slide has not occurred in that location before, that a scenario A event does not occur in the same year, and that a scenario A event has not occurred in a previous year. These various probabilities and assumptions are summarised in table 7.

Table 7 near here

Present values of expected benefits

We estimate the total benefits of the intervention over the expected 'project lifetime' which depends on the degree to which the drains and guttering are maintained. Blocked or cracked drains and disconnected or overflowing household connections will cause the infrastructure to be ineffective and to deteriorate more rapidly. Based on experience in this environment it is estimated that with maintenance the lifetime of such drains can be 20 to 25 years – if community residents continue to clean and maintain the drains and guttering properly. Without such maintenance, the drains may become ineffective after 7 or 8 years. We conservatively assume that if community residents do properly carry out maintenance, the landslide hazard reduction effects will last for 20 years, and if they do not, effects last for 7 years.

In order to calculate the present value of the expected costs of each landslide scenario, it is necessary to calculate the expected costs for each year in the future, and discount each year's value according to how far into the future that year is. For example, the discounted expected cost of landslides of type A in year t is:

$$\delta_t \; p_{A,t} \, c_A$$

Where δ_t is the discount factor for year t (equal to $1/(1+r)^t$, where r is the constant discount rate), $p_{A,t}$ is the probability that a landslide of type A will occur in year t,, and c_A is the cost of a landslide of type A. The present value of the expected costs from future landslides of type A is then:

$$p_{A,0} \, c_A \;+\; \delta_1 \, p_{A,1} \, c_A \;+\; \delta_2 \, p_{A,2} \, c_A \;+\; \ldots$$

It can be shown (see Appendix) that this is equal to:

$$\frac{q_{A,I} c_A \left(1-\left[(1-q_{A,I})/(1+r)\right]^N\right)}{1-\left[(1-q_{A,I})/(1+r)\right]} + \frac{q_A c_A \left[(1-q_{A,I})/(1+r)\right]^N}{1-\left[(1-q_A)/(1+r)\right]}$$

Where N is the number of years that the intervention's effects are expected to last and from table 7, $q_{A,I}$ (during the project lifetime) is 0.01 if the intervention has occurred, 0.1 otherwise, while q_A (*a*t the end of the projects' life) is 0.1.

It can also be shown (see Appendix) that the present value of the expected costs from future landslides of type B in location L is equal to:

$$\frac{q_{B,I} c_{B,L} (1-q_{A,I})\left(1-\left[(1-q_{A,I})(1-q_{B,I})/(1+r)\right]^N\right)}{1-\left[(1-q_{A,I})(1-q_{B,I})/(1+r)\right]} + \frac{q_B c_{B,L} (1-q_A)\left[(1-q_{A,I})(1-q_{B,I})/(1+r)\right]^N}{1-\left[(1-q_A)(1-q_B)/(1+r)\right]}$$

Where $c_{B,L}$ is the cost of a landslide of type B occurring in location L, q_B is 0.2, and $q_{B,I}$ is 0.02 if the intervention has occurred, 0.2 otherwise.

Given the total costs in table 6 the estimated direct benefits from landslide risk reduction (the difference in the expected costs associated with landslides with and without the intervention) are shown in tables 8a and 8b. With maintenance, the estimate benefits are **EC$ 304,211**; without maintenance, they are **EC$ 195,698**.

Tables 8a and 8b near here

3.3 Assessing indirect benefits

As well as the direct benefits in reducing landslide risk, the improved drainage and installation of roof guttering have the potential to bring about a number of additional benefits to the residents of the community. These include:

- savings in water bills through the harvesting of intercepted rainwater from the roofs
- improved access to and from the community due to reduced flooding and debris washed onto footpaths – making it easier to get to work and school
- reduced erosion and flood damage to property
- possible reduced mosquito population due to fewer mosquito-breeding sites

In cost-benefit analysis, the value of such benefits to individuals is captured by their willingness to pay (WTP) for the benefits, or their willingness to accept (WTA) compensation in the case of disbenefits (see Boardman et al, 2010, for example, for a comprehensive introduction). This can be measured either through revealed preference methods which attempt to find ways in which individuals directly or indirectly reveal their WTP (for example using wage rates as an indication of how much value individuals place on their time) or through stated preference methods (also known as contingent valuation methods) which directly ask people for their WTA/WTP. In this study a survey was carried out of each of the twenty households directly affected by the intervention to estimate total benefits using both approaches. The survey was undertaken by a locally-based technician with extensive experience in liaising with communities. Every household which had received roof-guttering and a connection to the new drains was surveyed (20 in total). These households had been selected for these mitigation measures on the basis of their contribution to the household and roof water which converged on the predicted (and previously observed) landslide locations. As such, the topography and geology constrained the zone of households included in the intervention. It was expected that these 20 households would all receive a degree of indirect benefit from this aspect of the intervention, whilst the CHASM analysis suggested that approximately half of these households would *directly* benefit from avoided future landslide losses. The interview, which took approximately 45 minutes to an hour to complete, was carried out with one member of each household.[2]

Revealed preference approach

The survey collected information on the residents and their households (used to determine the costs of rebuilding and of replacing possessions), and asked about a number of possible changes that residents might have experienced since the project was completed, including any changes in the time spent fixing their houses, in the time spent getting to work/school and in the number of days worked/ school attended, in water bills, and in mosquito nuisance or bites. This information was used to derive an estimate of the total benefits of the project to the community residents, based on revealed preference. As shown in table 9, the main quantified benefit is the value of more days worked. The other quantified benefit is that residents have lower water bills. In total these two quantified benefits are fairly sizeable – equal to around two-thirds of the estimates costs in the case

[2] The survey questionnaire is available from the authors on request.

of maintenance. This points to the fact that the project yields sizeable benefits to the local community residents, in addition to the obvious direct benefits associated with landslide risk reduction. This may be important in making a case for intervention. In addition to the quantified benefits, residents also derive benefit in a number of other ways – from less time spent fixing their homes, less time spent travelling to work and school. These estimates are presented in table 9 indicating how large the effects are, but a monetary value is not assigned because of the uncertainty surrounding the value to leisure time. The estimates are therefore likely to be an underestimate of the total benefits to community residents.

Table 9 near here

The main benefit identified in table 9 is the reduction in the number of days of work missed. During rainfall the paths in unplanned communities are often impassable due to surface runoff, localized flooding and the deposition of debris washed off the slope surface. Interviewees were asked whether the drainage intervention had improved the condition of the paths and whether this meant they had missed fewer days of work. Nine answered that they had missed one day fewer per month, one answered two days fewer, and nine said there had been no difference. One interviewee did not answer the question. In order to value the additional days worked, we assume a wage rate of EC$ 6.96 (the average minimum wage in St Lucia)[2] 3 per hour, and a working day of 8 hours. This gives us estimates of total working days and income saved for the community.

The second most important benefit was a reduction in the amount paid for mains water due to the increase in rainwater harvesting from the roofs of the houses (enabled by the installation of roof guttering and connection to water tanks). Interviewees were asked whether the amount they paid for mains water had fallen since the intervention. Six answered that they paid between 20 and 50 dollars less per month, another six answered that they paid between 5 and 20 dollars less per month, and 8 said there was no difference. One the basis of these survey responses, we can estimate the total saving in water bills. We use the minimum values of the ranges.

With respect to the decrease in localised flooding and erosion, interviewees were asked whether the time they needed to spend fixing their home had changed since the intervention. Fourteen interviewees answered that in the 6 months since the intervention had taken place, the time they had spent fixing their home was half a day less than it would have otherwise been. Five answered that it was 1 day less, and one answered that it was half a day *more*. We assume that this time saved (lost) is the total for the household, that it was (would have been) used for leisure, and that for every day spent fixing a home eight hours were actually spent. Since the choice of what value to place on leisure time is uncertain,[4] we choose not to place a monetary value on this time.

The reduced flooding was also hypothesized to have made it easier for residents to get to work or school during the rainy season. Interviewees were asked whether the time it took them to get to work each day had changed since the intervention. One interviewee answered no, but all others answered that there had been an improvement, with seven answering that their travel times had been reduced by less than 5 minutes, and twelve answering that their travel times had been reduced by 5 to 10 minutes. We assume that every adult who resides in a household which specified a difference of less than 5 minutes saves 30 seconds of travel time every day they travel to work. For adults whose household specified 5 to 10 minutes we assume a saving of 5 minutes. As with leisure, we choose not to assign a dollar value to this travel time, and exclude it from our final quantification of benefits. Similarly, interviewees were also asked whether the children of their household had missed fewer days of school. Three answered that their children had missed one day fewer per

[3] Based on St Lucian government data for 2003, available at http://www.stats.gov.lc/wagavg.htm and http://www.stats.gov.lc/main3.htm. We use the average minimum as a lower bound on the wage rate.

[4] Discussion

month, one answered two days fewer, and one said there was no difference. Four interviewees with children did not answer this question. We assume that each school child saves a school day for every day their household head says a school day has been saved. In principle, given a positive return to education, it would be possible to assign a monetary value to this additional schooling but, as with leisure and travel time saved, we choose not to include it in our monetary value of benefits.

The survey also indicated other, less easily quantifiable benefits. Twelve interviewees indicated that they had received fewer mosquito bites since the intervention, while two indicated they had received more. Eleven interviewees indicated that their environment was better, and one indicated that crime was down.

Stated preference approach

The survey also asked respondents whether they would be willing to make a contribution to the project – and how much they would pay, out of a banded set of amounts (see Appendix). All twenty interviewees indicated they would be willing to pay a certain amount each week, with two answering EC$ 1, four answering EC$ 5, eleven answering EC$ 10 and three answering EC$ 20. Using these individual responses we can derive a stated preference estimate of the total value of the indirect benefits (equal to the present discounted sum of the amount that individuals say they would be prepared to pay over the project lifetime). This is shown in table 10 below; it is assumed that the amount the interviewee specified is the total for their household which may cause us to understate the total benefits.

Although individuals are talking about a hypothetical payment, we have reason to believe that the responses to the stated preference questions are fairly reliable. First, there is some variation in individuals' responses according to household wealth. We would expect that wealthier households would be prepared to pay more for the project and we find that individuals in households with a higher level of possessions and more working adults say they would pay more. Secondly, there is also a positive relationship between how much individuals say they are prepared to pay and the estimated value of benefits for the household derived from the revealed preference approach. With only 20 households, it is not possible to do any systematic analysis of the responses, but this evidence points to the stated amounts being reasonable.

Using the stated preference approach, the estimated value of the indirect benefits is again fairly sizeable (equal to half the total costs in the case with maintenance). The stated preference approach gives an estimate of the total indirect benefits that is slightly lower than the revealed preference approach, but the two estimates are of a similar order of magnitude. The value of the two approaches is in providing a stronger evidence base that the intervention delivers real benefits to the residents of the community.

Table 10 near here

3.4 Sensitivity analysis

The magnitudes of the estimated costs and benefits in any CBA depend on the assumed parameter values. In this case, there are a number of key parameter values including the discount rate, the project lifetime and the hazard probabilities (with and without the intervention). In this section we demonstrate that our main result that benefits outweigh costs does not depend critically on our assumptions – we show, for each parameter that the critical value which would make benefits just equal to costs is well outside any reasonable range.

Table 11 near here

As already discussed, our chosen discount rate (a real rate of 12 per cent) is conservative, based on the upper limit of World Bank rates. The critical value for this parameter is 170 per cent.

The estimated project lifetime is already fairly conservative with respect to observed operational lifetimes of similar drains in such locations. The sensitivity analysis of this parameter indicates that were the project infrastructure to fail after only 3.3 years (as opposed to 20 years with maintenance, or 7 years without) then the benefits would equal the costs. This timeframe is actually coincident with the normal 3-4 year lifetime of development project cycles (the time taken from agreement of funding, to initiation, implementation and completion of a project). It could therefore be reasonably assumed that failure of the infrastructure within the wider project implementation phase might allow repairs to be carried out to further extend its service life. Regardless of this supposition, perhaps the key message of this aspect of the sensitivity analysis is that maintenance is vital in order to ensure that project benefits are realised.

The predicted probabilities associated with the two landslide scenarios are the product of a multifaceted (but standard) landslide hazard assessment process involving multiple slope parameters, rainfall data and modelling assumptions. As discussed in section 2, in this study the selection of 'best estimate' slope material parameter values was both conservative and in accord local knowledge of soils and other local modelling studies using CHASM (Anderson and Richards, 1987; Anderson et al., 2008). Previous studies have demonstrated that, when appropriately configured, CHASM is accurate in the quantification of landslide frequency (Anderson 1990) and robust with respect to physically realistic variations in soil parameters (Rubio et al., 2004). The third aspect of the sensitivity analysis considered the effect on the benefit-cost ratio if, *prior to the intervention*, the slopes were not as landslide-prone as predicted (table 11, row 3). Taking the slope stability in scenario A as an example, it is demonstrated that in order for benefits to equal costs, the slope stability prior to the intervention would need to be significantly higher – with the predicted landslide frequency decreasing from 1:10 years to 1:143 years. To effect such an increase in slope stability in CHASM would require potentially unrealistic deviations from the best estimate soil hydrology and strength parameter values.

Similarly, the fourth sensitivity test relates to the predicted landslide frequency – this time with respect to the modelled improvement in slope stability *after the intervention*. Using the best estimate parameters for CHASM and again considering scenario A, the drainage intervention decreases the probability of a landslide from a return period of 1:10 to 1:100 years – a reduction by a factor of 10 (table 11, column 2). The sensitivity analysis demonstrates that in order to cause project benefits to equal costs then the CHASM parameters would need to change such that the reduction in landslide probability drops from a factor of 10 to 1.29 – equivalent to a drop from the 1:100 year event to as low as a 1:14 years (table 11, column 3). It is important to reiterate that hydrological data and assumptions were conservative in that only a 35% reduction in effective rainfall was accounted for (the volume which could be accurately calculated given rainfall interception by the roofs of houses). Further reductions in effective rainfall due to surface water and grey-water capture were not modelled, but would be expected to improve slope stability even further. Therefore, given the already stated robustness of the CHASM model structure (Rubio et al., 2004), rainfall data and soil parameters (Anderson et al., 2008) this is considered a robust result in terms of demonstrating a positive benefit-cost ratio for the intervention.

4 Discussion

In order to build a culture of prevention and enable decision-makers to justify expenditure on landslide risk management in developing countries two key developments are vital: a strengthening of the evidence-base that landslide mitigation can pay, and the establishment of systematic methods for evaluating the effectiveness of mitigation as part of project cycles. With respect to the latter research niche, this study has achieved the integration of landslide risk assessment, mitigation and cost-benefit analysis methods in a systematic and realistic manner. Under conservative assumptions, an ex-post assessment of landslide mitigation measures has demonstrated a benefit-cost ratio of 2.7 to 1. We first summarise the methodological developments and project-specific findings before returning to the contribution of this study to the evidence-base that mitigation pays and to the wider DRR and development context.

The MoSSaiC approach to landslide risk reduction has already established that appropriate landslide mitigation measures can be delivered at the community level if slope processes and vulnerability are assessed (and addressed) at the correct scale (Anderson et al., 2008). In this study the development and application of an integrated landslide risk assessment and CBA methodology was grounded in the data acquired at this community scale – overcoming some of the methodological issues regarding scale, data availability and process-representation and allowing the degree of landslide risk (and risk reduction) to be quantified. This made it straightforward to estimate the direct benefits. In addition, conducting a survey of community benefits allowed us to estimate the indirect benefits of the project using both revealed preference and stated preference (contingent valuation) methods. These indirect benefits to the community were shown to be fairly substantial. This study also demonstrated the importance of maximising the service life of the drains and guttering through maintenance. Without maintenance it was estimated, using the stated assumptions, that the project lifetime would be reduced by nearly two-thirds – from 20 years to 7 years. The effect of lack of maintenance is to reduce the benefit-cost ratio from 2.7:1 to 1.7:1. The study site in this paper is representative of many unplanned settlements in the region in terms of the type of landslide hazard and the vulnerability of the community. It is proposed that the systematic approach developed for measuring the effectiveness of landslide mitigation projects will be applicable to future MoSSaiC projects – as either an ex-ante or ex-post project evaluation tool – and could potentially be adapted in other community-based DRR projects. Further application of the methodology developed here could involve the development of a range of idealised community 'test cases' comprising different combinations of hazard and vulnerability characteristics. This would provide an indication of typical cases in which landslide mitigation might be most effective from the dual perspectives of risk reduction (landslide costs avoided) and additional indirect benefits to the community.

The ability to assess longer term project outcomes is an important balance against the strong pressure for development practitioners to be upwardly accountable to donors by proving short term 'project outputs' (such as the number of households involved, metres of drain constructed, or amount of guttering installed). As Benson and Twigg (2004, p106) note "Most disaster reduction evaluations focus on outputs rather than outcomes or impact, partly due to their timing. Agency reports to donors are also predominantly activity-focused, with relatively little analysis of outcomes (and often some rather tenuous linking of output to outcome)." Thus whilst providing the necessary evidence base for decision-makers, the development of a hazard-specific, project level methodology also provides a degree of downward accountability (from the implementing agency to the community) by considering longer-term outcome and indirect project benefits to the community.

In the wider decision-making context this study has provided evidence that landslide risk reduction is a viable option for governments and international development agencies to incorporate into DRR and development programmes. By adopting a quantitative and transparent approach it is believed that this form of evidence offers decision-makers a more defendable basis for endorsing DRR both at the project level and with respect to wider development policy and funding programme. A second important message is that within the context that 'mitigation pays' there is a strong case to be made that 'maintenance pays'. Thus, for every mitigation project it is vital to consider who is going to invest in maintenance of the new measures. Finally, it is hoped that while this study contributes to the process of 'awareness raising' its main messages can be conveyed through the *demonstration* that physically landslide mitigation measures can be delivered on the ground in the most vulnerable communities, and that there is evidence that that they are effective.

Appendix A1: Household survey questionnaire

MOSSAIC PROJECT DRAFT COMMUNITY QUESTIONNAIRE

INTERVIEWER SAY: The reason for this questionnaire is to work out how much difference the drainage project has made to people in this community. The first two parts of the questionnaire will help give a picture of life in your household and how much a landslide might affect you. The other parts of the questionnaire will look at whether the project has been effective in reducing problems caused by flooding and landslides.

SECTION 1 THE HOUSEHOLD

Household profile:

1. Number of people in household

- Adults – senior citizens ☐
- Adults – working age ☐
- Children – secondary school / college age ☐
- Children – primary school age ☐
- Babies and infants ☐

2. Number of children attending school

- Number at secondary school / collage ☐
- Number at primary school ☐

3. Highest educational qualifications of head

- O Tertiary / university
- O Secondary complete
- O Secondary incomplete
- O Primary complete
- O Primary incomplete
- O None

4. Employment status of adults

- Number of adults working – permanent job ☐
- Number of adults working – intermittent ☐
- Number of adults not working ☐

5. How long have you been living in the community?

☐ O months O years

Questions relating to accommodation

6. Tenure

- O Owned land and house
- O Rented land (built own house on land)
- O Rented land and house

7. Number of bedrooms

- Number of bedrooms ☐

8. Wall type

- O Brick / block / concrete
- O Wood and concrete
- O Wood
- O Wattle / Tapia / Makeshift

9. Toilet type

- O WC to sewer / septic tank
- O Pit latrine / none

10. Light source

- O Electricity
- O Kerosene / none

11. Household possessions

- O TV
- O Telephone
- O Video / DVD
- O Stove
- O Fridge
- O Washing machine
- O Car / pick-up

Direct benefits from project

12. Physical benefits

- O Drain adjacent to house
- O Footpath access to house
- O Roof guttering and downpipes
- O Water tank

13. Employment on project

- O Awarded contract for construction / installation
- O Employed by contractor as mason / carpenter
- O Employed by contractor as labourer
- Number of days employed ☐

SECTION 2 REPLACEMENT COST OF HOUSE AND ITEMS

14. Do you have any insurance to pay for replacement of things or to cover the cost of damage to your property?
- O Yes – contents only
- O Yes – building only
- O Yes – contents and building
- O No

If yes:

15. Can you tell me roughly how much you are paying?
To the nearest EC dollar

$ | | | | | | O per month O per year

If no:

16. Thinking about everything that you own (your cooker, stereo, tv etc.), how much do you think it would cost to replace it all if you had to start from scratch?
To the nearest EC dollar

$ | | | | | |

If you're not sure, then is it between:
- O 0 and 1000 dollars
- O 1000 and 10,000 dollars
- O 10,000 and 50,000 dollars
- O over 50, 000 dollars

17. Suppose you could get insurance that would pay you this amount if something happened. How much would you pay?
- O Nothing
- O 1 dollar a week
- O 5 dollars a week
- O 10 dollars a week

SECTION 3 IMPROVEMENTS IN EVERYDAY LIFE

INTERVIEWER SAY: I would like to ask you about some of the things that may have changed around here since the drainage project was carried out. When you answer, you will need to think about how things are now compared to how they were before the project started.

Flooding and damage to property

First think about what happens when it rains heavily.

18. Would you say there is:
- O About the same level of flooding by your house as there was before the project
- O More flooding than there was
- O Less flooding than there was

If more / less:

19. Has this affected how much time you need to take fixing your home?
- O Spent more time
- O Spent less time
- O Spent about the same time

20. Roughly how much more or less time would you say that you have spent?
- O Half a day
- O About a day
- O Two days
- O More than two days

Mosquitoes and Health

One of the possible benefits of the drainage project is to reduce the amount of standing water where mosquitoes breed. Mosquitoes can simply cause a nuisance, but they can also cause skin problems and illnesses like dengue fever.

21. Would you say that you have been bitten by mosquitoes:
- O About as much as before the drainage project
- O More than before the drainage project
- O Less than before the drainage project

If more / less mosquito bites:

22. And has this changed the number of days of work missed through mosquito-borne illnesses?
- O I have missed fewer days of work
- O I have missed more days of work
- O I have missed about the same amount of work

If more / less days off work:

23. How many more / fewer days have you missed in the last month?

- ○ One day
- ○ Two days
- ○ Three days
- ○ A week

24. What about your children, have they missed more / fewer days of school through mosquito-borne illnesses?

- ○ They have missed fewer days of school
- ○ They have missed more days of school
- ○ They have missed the same amount of school

If more / less days off school:

25. How many more / fewer days have they missed in the last month?

- ○ One day
- ○ Two days
- ○ Three days
- ○ A week

Improved access

I'd now like you to think about how easy it is to get from your house to the road and back when it rains and the paths get muddy.

26. Would you say that:

- ○ There has been no change in how easy it is to get to my home since the drainage project (go to next section on water harvesting).
- ○ It is easier since the drainage project
- ○ It is harder since the drainage project

27. Why do you think it's easier or harder to get to your home now? (Tick as many as apply)

- ○ It's easier because the project included some new concrete paths
- ○ It's easier because the previously existing paths stay drier and don't flood
- ○ It's harder because the paths flood more

28. And has this meant it has taken less / more time to get to work?

- ○ It has been quicker to get to work and school
- ○ It has been slower to get to work and school
- ○ It has taken the same time to get to work and school

If quicker / slower:

29. How many quicker / slower?

- ○ Less than 5 minutes different
- ○ 5 to 10 minutes different
- ○ More than 15 minutes different

30. Are you missing more / fewer days of work?

- ○ I have missed fewer days of work
- ○ I have missed more days of work
- ○ I have missed about the same amount of work

If more / less days off work:

31. How many more / fewer days have you missed in the last month?

- ○ One day
- ○ Two days
- ○ Three days
- ○ A week

32. What about your children, have they missed more / fewer days of school because of the effect of the drainage project on the paths?

- ○ They have missed fewer days of school
- ○ They have missed more days of school
- ○ They have missed the same amount of school

If more / less days off school:

33. How many more / fewer days have they missed in the last month?

- ○ One day
- ○ Two days
- ○ Three days
- ○ A week

Water Harvesting and WASCO Water Supply

I'd like you to think about your water supply before and after the drainage project.

34. Before the project did you have roof guttering?

- ○ Yes, roof-guttering for the whole roof
- ○ Yes, roof-guttering for part of the roof
- ○ No roof-guttering

35. Before the project did you collect roof water?

- ○ Yes, the roof water went into water containers
- ○ No, the roof water went to a drain
- ○ No, the roof water went on the ground

36. Did you receive roof guttering, down-pipes or a water tank as part of the drainage project?

- ○ Yes, roof guttering, down-pipes and water tank
- ○ Yes, roof guttering and down-pipes
- ○ Yes, just roof guttering
- ○ Yes, just down-pipes
- ○ No, nothing

If now collecting roof water:

37. Can you think about how much you pay for WASCO water now compared to how much you paid before the drainage project.

- ○ Pay the same as before the drainage project
- ○ Pay less than before the drainage project
- ○ Pay more than before the drainage project

If paying more / less:

38. How much more / less do you pay for WASCO water per month?

To the nearest EC$

$ | | | | |

- ○ More
- ○ Less

If you're not sure, then is it between:

- ○ 0 and 5 dollars
- ○ 5 and 20 dollars
- ○ 20 and 50 dollars
- ○ More than 50 dollars

Other changes since the drainage project

Use this space to list any other positive or negative changes before and after the project

(*prompt*: such as changes in crime levels due to better access, changes in general environment – cleaner / dirtier…)

SECTION 4 VALUE OF THE LANDSLIDE AND DRAINAGE PROJECT

Suppose that it was the community that had to pay for the project to take place, and not the Government, and you were asked to make a voluntary contribution or pay something towards the project cost.

39. Would you be willing to pay something?

- ○ Yes (go to question 40)
- ○ No (go to question 41)

If yes:

40. Roughly how much would you be willing to pay?

- ○ 1 dollar a week
- ○ 5 dollars a week
- ○ 10 dollars a week
- ○ 20 dollars a week

If no:

41. Why wouldn't you be willing to pay?

- ○ I can't afford to
- ○ I don't want to

42. Instead of giving money, would you be prepared to work on the project even if you weren't getting paid anything?

- ○ Yes (go to question 43)
- ○ No (go to question 44)

If yes:

43. Roughly how much would you be willing to work?

- ○ Half a day
- ○ One day
- ○ Two days
- ○ A week
- ○ Two weeks
- ○ One month

If no:

44. Why wouldn't you be willing to work?

- ○ I can't afford to
- ○ I don't want to

Appendix A2: Deriving the present value of the expected costs of landslides of different types

Probabilities

Let:

$p_{A,t}$	=	probability of a landslide of type A occurring in year t
$p_{B,L,t}$	=	probability of a landslide of type B occurring in location L in year t
q_A	=	0.1
q_B	=	0.2
$q_{A,I}$	=	0.01 if intervention has occurred, 0.1 otherwise
$q_{B,I}$	=	0.02 if intervention has occurred, 0.2 otherwise
N	=	project lifetime

Assume:

$$p_{A,t} = \begin{cases} q_{A,I} & \text{if } 0 \leq t \leq N-1\text{, and no landslide of type } A \text{ in year } i\text{, for all } i < t \\ q_A & \text{if } t \geq N\text{, and no landslide of type } A \text{ in year } i\text{, for all } i < t \\ 0 & \text{otherwise} \end{cases}$$

$$p_{B,L,t} = \begin{cases} (1 - q_{A,I})\, q_{B,I} & \text{if } 0 \leq t \leq N-1\text{, and no landslide of type } A \text{ in year } i\text{, and no landslide of type } B \text{ in location } L \text{ in year } i\text{, for all } i < t \\ (1 - q_A)\, q_B & \text{if } t \geq N\text{, and no landslide of type } A \text{ in year } i\text{, and no landslide of type } B \text{ in location } L \text{ in year } i\text{, for all } i < t \\ 0 & \text{otherwise} \end{cases}$$

That is, a landslide of type A may occur at most once – once it has occurred, the landscape is sufficiently altered that it may not occur again. The same goes for a landslide of type B: there are three locations in which this type of landslide may occur, and once it has occurred in a particular location, it may not occur in that location again. An additional restriction is that a landslide of type A affects the entire area in which landslides of type B may occur: once a landslide of type A has occurred, no landslide of type B may occur in any location. It is further assumed that if a landslide of type A occurs in a given year, no landslide of type B occurs that year.

Then prior probabilities are:

$$p_{A,t} = \begin{cases} (1 - q_{A,I})^t \, q_{A,I} & \text{for all } 0 \leq t \leq N\text{–}1 \\ (1 - q_{A,I})^N (1 - q_A)^{t-N} \, q_A & \text{for all } t \geq N \end{cases}$$

$$p_{B,L,t} = \begin{cases} (1 - q_{A,I})^t (1 - q_{B,I})^t (1 - q_{A,I}) \, q_{B,I} & \text{for all } 0 \leq t \leq N\text{–}1 \\ (1 - q_{A,I})^N (1 - q_{B,I})^N (1 - q_A)^{t-N} (1 - q_B)^{t-N} (1 - q_A) \, q_B & \text{for all } t \geq N \end{cases}$$

Present values

Let:

r = discount rate (constant)

δ_t = discount factor for year t = $1 / (1 + r)^t$

c_A = Cost of a landslide of type A occurring

$c_{B,L}$ = Cost of a landslide of type B occurring in location L

$\text{PV}_{A,y}$ = Present value of expected costs from landslides of type A occurring in year y

$\text{PV}_{B,L,y}$ = PV of expected costs from landslides of type B occurring in location L in year y

Then:

$$\text{PV}_{A,t} = \delta_t \, p_{A,t} \, c_A = p_{A,t} \, c_A / (1 + r)^t$$

And:

$$\text{PV}_{B,L,t} = \delta_t \, p_{B,L,t} \, c_{B,L} = p_{B,L,t} \, c_{B,L} / (1 + r)^t$$

So the **present value of expected costs from landslides of type *A*** is:

$$[\, \text{PV}_{A,0} + \text{PV}_{A,1} + \ldots + \text{PV}_{A,N\text{-}1} \,] + [\, \text{PV}_{A,N} + \text{PV}_{A,N+1} + \ldots \,]$$

$$= [\, p_{A,0} \, c_A + \delta_1 p_{A,1} \, c_A + \ldots + \delta_{N\text{-}1} p_{A,N\text{-}1} \, c_A \,] + [\, \delta_N \, p_{A,N} \, c_A + \delta_{N+1} p_{A,N+1} \, c_A + \ldots \,]$$

$$= [\, q_{A,I} \, c_A + q_{A,I} \, c_A \, (1 - q_{A,I})/(1 + r) + \ldots + q_{A,I} c_A \, (1 - q_{A,I})^{N\text{-}1}/(1 + r)^{N\text{-}1}] + [\, q_A \, c_A \, (1 - q_{A,I})^N/(1 + r)^N + q_A c_A \, (1 - q_A) \, (1 - q_{A,I})^N / (1 + r)^{N+1} + \ldots \,]$$

Which is a pair of geometric series, and so:

$$= \frac{q_{A,I} c_A \left(1 - \left[(1 - q_{A,I})/(1 + r)\right]^N\right)}{1 - \left[(1 - q_{A,I})/(1 + r)\right]} + \frac{q_A c_A \left[(1 - q_{A,I})/(1 + r)\right]^N}{1 - \left[(1 - q_A)/(1 + r)\right]}$$

And the **present value of expected costs from landslides of type *B* in location *L*** is:

$$[\,\mathrm{PV}_{B,L,0} + \mathrm{PV}_{B,L,1} + \ldots + \mathrm{PV}_{B,L,N\text{-}1}] + [\,\mathrm{PV}_{B,L,N} + \mathrm{PV}_{B,L,N+1} + \ldots\,]$$

$$= [\,p_{B,L,0}\; c_{B,L} + \delta_1 p_{B,L,1}\; c_{B,L} + \ldots + \delta_{N\text{-}1}\; p_{B,L,N\text{-}1}\; c_{B,L}\,] + [\,\delta_N\, p_{B,L,N}\, c_{B,L} + \delta_{N+1} p_{B,L,N+1}\; c_{B,L} + \ldots\,]$$

$$= [q_{B,I}\; c_{B,L}\;(1 - q_{A,I}) + q_{B,I}\; c_{B,L}\;(1 - q_{A,I})(1 - q_{A,I})(1 - q_{B,I})/(1 + r) + \ldots + q_{B,I}\; c_{B,L}\;(1 - q_{A,I})(1 - q_{A,I})^{N\text{-}1}(1 - q_{B,I})^{N\text{-}1}/(1 + r)^{N\text{-}1}\,] +$$

$$[q_B\; c_{B,L}\;(1 - q_A)(1 - q_{A,I})^N(1 - q_{B,I})^N/(1 + r)^N + q_B\; c_{B,L}\;(1 - q_A)(1 - q_{A,I})^N(1 - q_{B,I})^N(1 - q_A)(1 - q_B)/(1 + r)^{N+1} + \ldots\,]$$

Which is a pair of geometric series, and so:

$$= \frac{q_{B,I}c_{B,L}(1-q_{A,I})\left(1-\left[(1-q_{A,I})(1-q_{B,I})/(1+r)\right]^N\right)}{1-\left[(1-q_{A,I})(1-q_{B,I})/(1+r)\right]} + \frac{q_B c_{B,L}(1-q_A)\left[(1-q_{A,I})(1-q_{B,I})/(1+r)\right]^N}{1-\left[(1-q_A)(1-q_B)/(1+r)\right]}$$

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Tables

Table 1 Soil parameters used in CHASM simulation of study site slope stability

Strata depth (m) relative to overall slope of 30°	Material weathering grade and description	Cohesion, c (-)	Angle of internal friction, ϕ (degrees)	Saturated hydraulic conductivity, K_{sat} (ms^{-1})
0-5	Grade 6 residual soil	4	25	$1e^{-5}$
5-10	Grade 4 weathered bedrock	20	30	$1e^{-6}$
10+	Grade 1 bedrock	30	40	$1e^{-8}$

Table 2 Estimated damage to houses as a result of the two landslide scenarios modelled in CHASM

Two landslide hazard scenarios		**Four damage scenarios identified in section 2.1 (damage potential 0 to 1) and house construction type for use in calculation of rebuilding cost**			
		House damaged (0.5), Possessions intact (0)	**House lost (1), Possessions intact (0)**	**House damaged (0.5), Possessions lost (1)**	**House lost (1), Possessions lost (1)**
Scenario A: Progressive shallow failures affecting whole slope		2 concrete 1 wood	3 wood/concrete 2 wood	-	1 wood/concrete 2 wood
Scenario B: Separate minor failures	Location 1	-	1 wood	1 wood	-
	Location 2	-	1 wood/concrete	1 wood/concrete	-
	Location 3	-	1 wood/concrete	1 wood/concrete	-

Table 3 24-hour design storms: return periods, intensities and effect on slope stability before and after the installation of roof guttering and its connection to the new drains

Rainfall return period, years (probability)	Effective rainfall intensity, mmh^{-1}		Slope stability (x =predicted landslide)			
	before intervention	after roof guttering installed	Scenario A: whole slope X_1-X_2		Scenario B: cut slopes Y_1-Y_2	
			before	after	before	after
1:1.5 (0.67)	5	3.25	✓	✓	✓	✓
1:5 (0.2)	7.62	4.953	✓	✓	x	✓
1:10 (0.1)	9	5.85	x	✓	x	✓
1:20 (0.05)	10.5	6.825	x	✓	x	✓
1:50 (0.02)	12	7.8	x	✓	x	x
1:100 (0.01)	14	9.1	x	x	x	x

Table 4 Estimated costs and benefits of landslide risk reduction at the study site

	With maintenance	**Without maintenance**
Initial costs	150,000	150,000
Estimated cost of maintenance	3,602	-
PRESENT VALUE, ESTIMATED COSTS	153,602	150,000
Benefits of risk reduction	304,211	195,698
Benefits for community residents	106,286	64,940
PRESENT VALUE, ESTIMATED BENEFITS	410,497	260,638
NET PRESENT VALUE	256,895	110,638

Notes to table: All values in XCD (EC$, Eastern Caribbean Dollars);
Real discount rate = 0.12, Effects assumed to last 20 years with maintenance, 7 without

Table 5 Summary of initial project costs and ongoing maintenance costs

Initial project costs				
Materials	Labour from inside community	Labour from outside community	Possible other costs	Total initial costs
105,000	27,200	6,400	11,400	**150,000**

Maintenance costs		
Number of hours of work per year	Estimated cost per year	Estimated present value
52	431	**3,602**

Notes to table: All values in EC dollars;
Real discount rate = 0.12, Effects assumed to last 20 years with maintenance, 7 without

Table 6 Estimation of landslide costs for the two landslide scenarios

Landslide scenario		**Costs from lost houses**	**Costs from damaged houses**	**Costs from lost possessions**	**Total cost**
A: Progressive shallow failures affecting whole slope		EC$ 499,680	EC$ 30,000	EC$ 33,900	EC$ 563,580
B: Minor failure in particular location	Location 1	EC$ 57,460	EC$ 10,000	EC$ 11,300	EC$ 78,760
	Location 2	EC$ 67,460	EC$ 10,000	EC$ 11,300	EC$ 88,760
	Location 3	EC$ 67,460	EC$ 10,000	EC$ 11,300	EC$ 88,760

Table 7 Assumptions used in the generation of annual landslide probabilities for incorporation into CBA

Probability		**Intervention in effect**	**Intervention not in effect**
That a type A landslide will occur in a given year if:	no type A landslide has occurred before	0.01	0.1
	Otherwise	0	0
That a type B landslide will occur in a given year in a given location if:	no type B landslide has occurred before in the same location & no type A landslide has occurred before & no type A landslide occurs in the same year	0.02	0.2
	Otherwise	0	0

Table 8a Expected benefits from landslide risk reduction – with maintenance

Landslide scenario		**Present value of expected costs**		**Difference = estimated benefits**
		with intervention	without intervention	
A: Progressive shallow failures affecting whole slope		EC$ 68,765	EC$ 286,913	EC$ 218,148
B: Minor failure in particular location	Location 1	EC$ 13,246	EC$ 39,695	EC$ 26,449
	Location 2	EC$ 14,928	EC$ 44,735	EC$ 29,807
	Location 3	EC$ 14,928	EC$ 44,735	EC$ 29,807
Discount rate = 0.12, Intervention's effects last 20 years				

Table 8b Expected benefits from landslide risk reduction – without maintenance

Landslide scenario		**Present value of expected costs**		**Difference = estimated benefits**
		with intervention	**without intervention**	
A: Progressive shallow failures affecting whole slope		EC$ 149,051	EC$ 286,913	EC$ 137,862
B: Minor failure in particular location	Location 1	EC$ 21,921	EC$ 39,695	EC$ 17,774
	Location 2	EC$ 24,704	EC$ 44,735	EC$ 20,030
	Location 3	EC$ 24,704	EC$ 44,735	EC$ 20,030
Discount rate = 0.12, Intervention's effects last 7 years				

Table 9 Indirect additional benefits to the community using the Revealed Preference Approach

Benefit		**Assigned dollar value per year**	**Net present value with maintenance**	**Net present value without maintenance**
Fewer days of work missed: working days saved per year	196 working days	EC$ 10,905	EC$ 91,228	EC$ 55,739
Lower water bills: savings per year	EC$ 1,800	EC$ 1,800	EC$ 15,058	EC$ 9,201
Less time spent fixing home: leisure time gained per year	184 hours	EC$ 0	-	-
Less time spent travelling to work: travel time saved per year	334 hours	EC$ 0	-	-
Fewer days of school missed: school days saved per year	108 school days	EC$ 0	-	-
Total benefits		EC$ 12,705	**EC$ 106,286**	**EC$ 64,940**

Discount rate = 0.12, Intervention's effects last 20 years with maintenance, 7 without

Table 10 Indirect additional benefits to the community using the Stated Preference Approach

Willingness to pay per week (total for community)	Willingness to pay per year (total for community)	Present value, if willing to pay every year for duration of intervention's effects (with maintenance)	Present value, if willing to pay every year for duration of intervention's effects (without maintenance)
EC$ 192	EC$ 9,984	EC$ 76,747	EC$ 49,198
Real discount rate = 0.12, Intervention's effects last 20 years with maintenance, 7 without			

Table 11 Sensitivity of cost-benefit analysis parameters

Parameter	**Central assumption used in study**	**Critical value at which benefits = costs**
1. **Discount rate**	**0.12**	**1.7**
2. **Project lifetime**	**20** years with maintenance (7 years without)	**3.3** years
3. **Initial hazard** Probability of landslide before intervention for scenarios A and B	Before intervention q_A = **0.1** and q_B = **0.2** (1:10 and 1:5 years)	Before intervention q_A = **0.007** and q_B = **0.014** (1:143 and 1:71 years)
4. **Hazard reduction** Magnitude of reduction in probability of landslide after intervention for scenarios A and B	Reduction in probability by factor of **10** Thus, $q_{A,I}$ = 0.01 and $q_{B,I}$ = 0.02 (1:100 and 1:50 years)	Reduction in probability by factor of **1.29** Thus, $q_{A,I}$ = 0.07 and $q_{B,I}$ = 0.155 (1:14 and 1:6.5 years)

Figures

Fig. 1 Typical unplanned housing location, construction type and density in the Caribbean

Fig. 2 Plan of study site showing location of drains constructed to capture surface runoff and roof water

Fig. 3 The components of the integrated model of landslide risk assessment, risk reduction and cost benefit analysis developed for this study

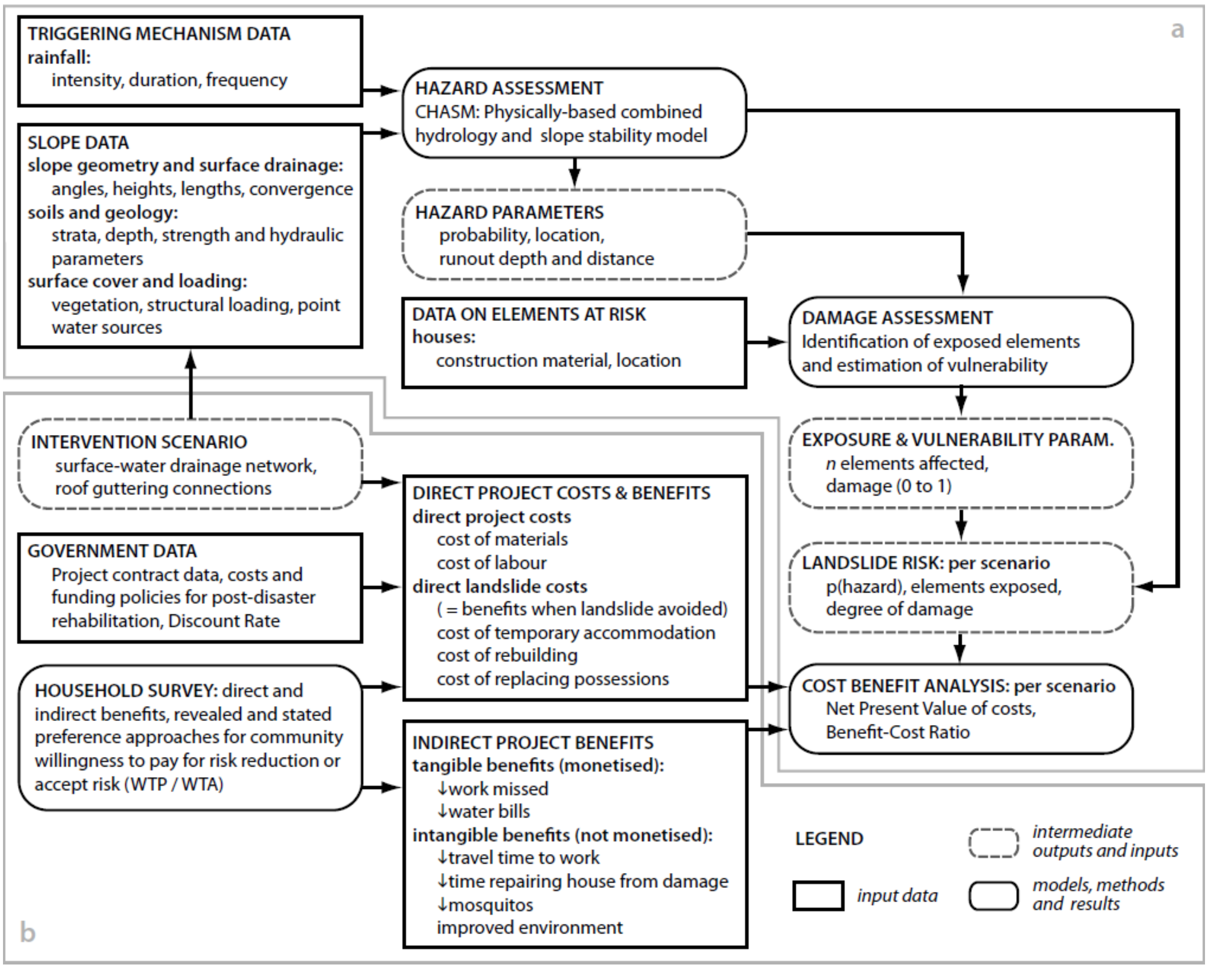

Fig. 4 Typical wooden house reconstructed (on its original site) after damage by a landslide in the cut slope above

Fig. 5 Scenario A: cross-section (X_1-X_2) showing the location of progressive landslide slip surfaces (predicted using CHASM), estimated debris runout and assumed damage to houses

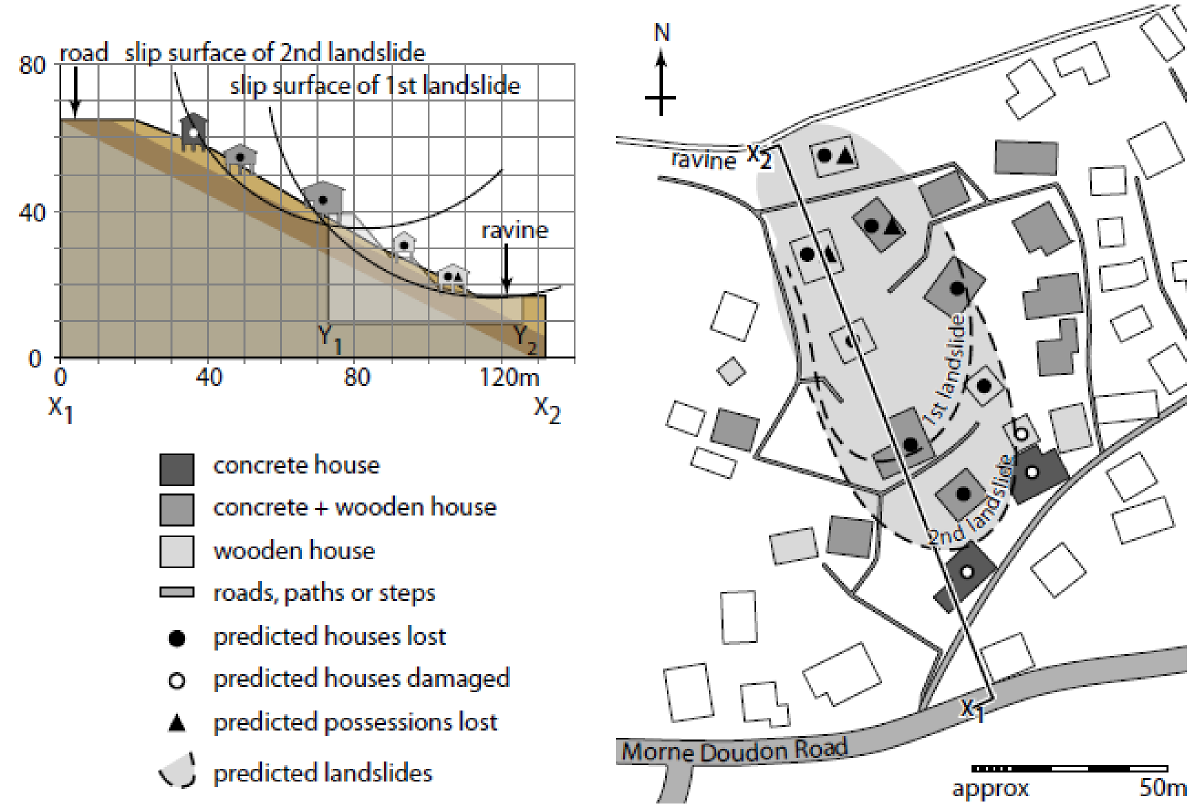

Fig. 6 Scenario B: cross-section (Y_1-Y_2) showing the locations of minor landslides in cut slopes (predicted using CHASM), estimated debris runout and assumed damage to houses

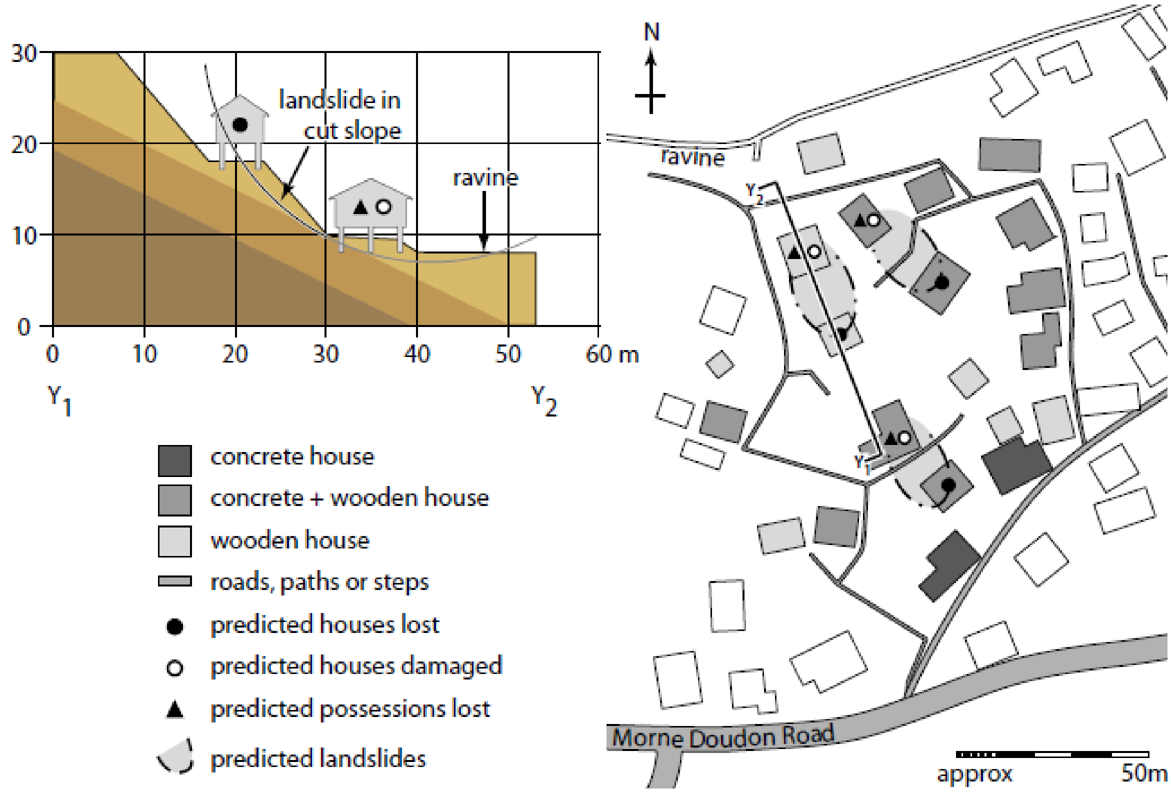

Fig. 7 Scenario A: Effect of 1 in 10 year, 24-hour rainfall on the stability of the slope (Factor of Safety) at cross-section X1-X2, where F≤1 indicates slope failure (for the ‘no intervention’ case assume slope failure at time=273 when F=1.01)

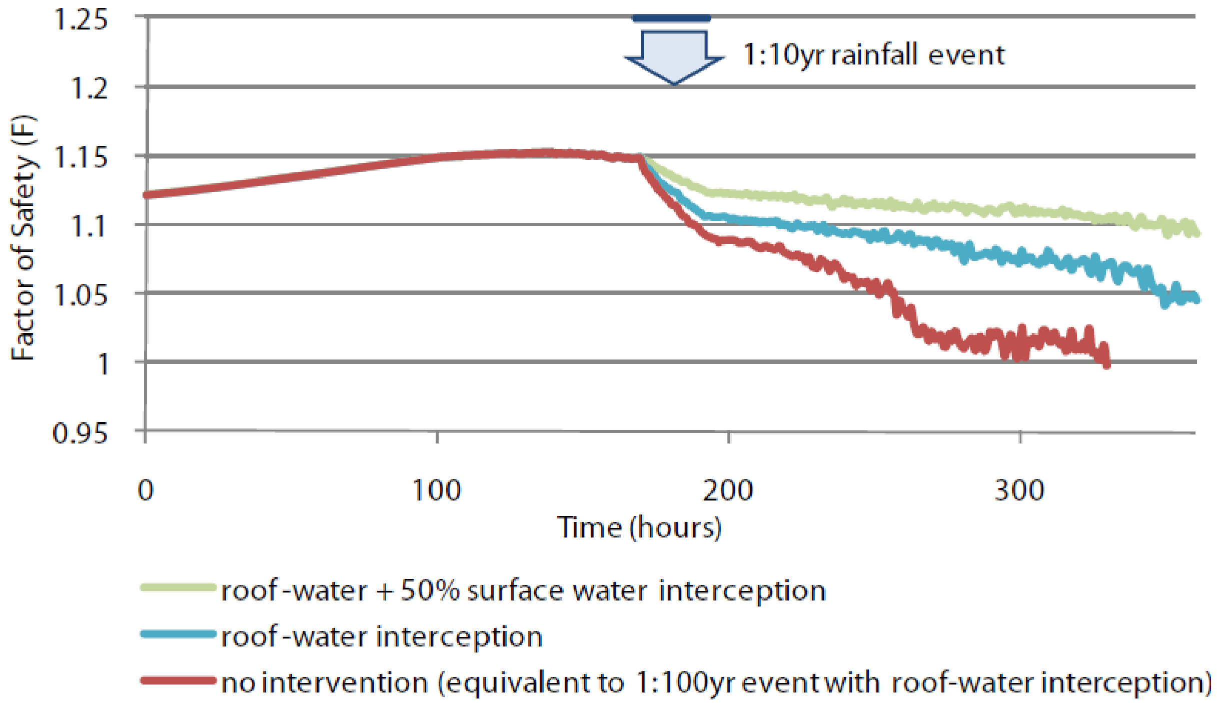

Fig. 8 Scenario B: Effect of 1 in 5 year, 24-hour rainfall on the stability of the slope (Factor of Safety) at cross-section Y_1-Y_2, where $F \leq 1$ indicates slope failure (for the 'no intervention' case assume slope failure at time=195 when F=1.01)