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Development of methodology for quantitative landslide risk assessment—Example Göta river valley

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ABSTRACT

Effective landslide risk management requires knowledge of the landslide risks. This paper presents a risk assessment methodology for semi-regional scale. The landslide probability is assessed taking into account expected climate-change in the case study area (the Göta river valley). Climate change is expected to result in increased erosion and water fluctuations. There are large areas with marine clays, often quick clay, in the area and the landslide process can be rapid with extensive damages and casualties. The consequence methodology includes a wide range of consequences assessed by monetary valuation. The consequences and the landslide probability are combined as pairs of values in a risk matrix and the risk is also presented on a map. The map has been used as discussion and decision bases in the municipalities in the Göta river valley, in the county administration and on governmental level to estimate the needs of risk mitigation and to make priorities.

KEYWORDS

Landslide; Risk Assessment; Methodology; Climate Change

1. INTRODUCTION

Climate change is expected to cause severe impacts on the natural and built environment. In addition to the temperature increase per se, climate change is expected to profoundly influence the hydrology, e.g. [1]. In Norway, Sweden and Northern Europe, the annual precipitation is expected to increase by up to 30% in the period 2071-2100 compared to the reference period 1961-1990 [2-4]. The river runoff is in general expected to be higher in winter, followed by a less pronounced snowmelt peak and lower summer flows [4]. The summers will be dryer but, regardless of season, the predictions indicate an increase of intensive rainfall and extreme flows [3,4]. The changes will lead to increased erosion rate and also other impacts that will affect the slope stability such as water level changes and changes in vegetation, e.g. [1,5]. One of the conclusions in the Swedish climate and vulnerability inquiry [6] was that the increased risks related to erosion and landslides will increase in the coming decades to such an extent that adaptation measures are needed to be taken already today.

Land slide events, such as other natural hazard events, are not disasters per se but the consequences may be-severe and even disastrous [7-13]. In technical risk analysis, the landslide risk is therefore referred as a function of the probability of a landslide event and the consequences thereof and the risk can be mitigated by either reducing the probability, the consequences of an event or both, e.g. [8,14-17].

For a well-functioning risk mitigation strategy, the risk mitigation requirement needs to be determined. The risk mitigation requirement is a function of the relation between the results of a risk assessment and the accepted level of risk, e.g. [8,17,18]. The risk assessment is done by assessing the probabilities of the unwanted events, e.g. landslides, and assessing the consequences of each event.

The causes of landslides are site specific and complex. The cause can be both primary (caused by factors that are long lasting and inherent in the constituent rock and the soil) and caused by triggers (factors that are varying or very short lived), e.g. [13]. Due to the wide range of landslide processes, the annual probability and the extension of a potential landslide are difficult to assess and the environmental and societal context is crucial for determining the specific effects on the vulnerability as pointed out by Andersson-Berry & King [19] and Roberts *et al*. [17]. The examples of quantitative assessments of landslide probability reported in the literature have been sited specific and based on statistical information combined with ground properties and parameter uncertainty analysis [11,20-25].

The consequence is a function of the amount of elements at risk (the numbers exposed) and the vulnerability of the affected element or system at risk [22]. Vulnerability is the degree to which a system is susceptible to, or unable to cope with the situation. It can be defined as a function of the character, magnitude and rate of the event to which a system is exposed, its sensitivity, and its adaptive capacity [5,26], or in other words the exposure to the event (perturbation and stresses) combined with the sensitivity and resilience and adaptive capacity of the system [13,14,16,26-28]. Even though the landslide probability is complex to determine the vulnerability, it is even more complex that there is no generic method for assessing the sensitivity, resilience and adaptive capacity for all types of elements at risk. For some impacts, quantitative assessment is possible while for others only qualitative assessments are preferable [8].

Landslide risk (R) is, as described above, referred to as a function of probability and the consequence of a landslide. Recently it often also includes the costs related to the event, *i.e.* R = H*V*E where, H is the land hazard (landslide) probability, V is the physical vulnerability in case of an event and E is the cost of the particular elements at risk, e.g. [23]. To involve the cost in the risk, assessment function is relevant when assessing the costs and benefits of risk mitigation. As pointed out by van Westen *et al*. [29] and Crovelli and Coe [23], although the risk equation is simple, it is difficult to be applied in practise due to difficulties in determining H, V and E. Yet, the ability to forecast losses is critical for effective landslide risk management.

Despite the difficulties, cost benefit analyses (CBA) have recently been performed on numerous risk management options, *i.e.* physical measures [30], landslide susceptibility mapping [20], warning systems and physical measures, the efficiency of incorporating risk mitigation in local comprehensive plans [9] and risk reduction programs [31]. Crovelli and Coe [23] estimated the number of future landslides for a given time period and the economic losses from those landslides, based on historical landslide costs (losses) to assess the expected costs in the San Francisco bay region. The results can be, and were, applied for future prognosis but also to relate the costs to other regions. Similar future cost estimates have been done as presented in [10,20,22,32-36]. In such analyses, the consequence assessments are generally based on loss of life and material (buildings) including reconstruction and renovation costs. In some assessments, losses of income due to delays or closures are included [37]. In general, sensitivity and time-dependent exposure are not taken into account. In some countries, like Sweden, there are not enough data that can be applied for statistically based landslide prognoses [38]. Instead the probability needs to be assessed based on field measurements of the current situation combined with slope stability calculations. On the other hand, Sweden has a wealth of data when it comes to consequence analysis.

The aim of this paper is to present a quantitative landslide risk assessment methodology developed for semi-regional scale such as a large run-off area and taking into account a wide range of consequences. The method has been applied for assessing the risk, in the Göta river valley, a large river system in one of Sweden's most landslide-prominent areas [39,40]. The work was initiated by the Swedish Government in response to the results of the Swedish climate and vulnerability inquiry [6]. The risk assessment is in Swedish referred to as Göta älvutredningen [41].

2. METHOD

2.1. The Study Area

The Göta river valley runs from Lake Vänern in thenorth to Göteborg in the south (**Figure 1**). The valley is one of the most frequent landslide valleys in Swede [39,40] with a number of landslides occurring every year. In general the landslides are fairly small, shallow and caused by erosion. Larger landslides have also occurred in the river valley resulting in human casualties and extensive property damage [39].

Geologically the prerequisites for landslides formed during and following the latest glaciation period, whendeep layers of clay formed in the river valley which wassubmerged in the sea during this period. Since the material was mainly deposited in a marine environment, quick clay is common in the area. Quick clay is a soil with high water content and weak bindings between the clay particles. Vibrations, or a small initial landslide, can cause a quick clay layer to collapse and liquefy, resulting in a large rapid landslide [42]. The river flow is regulated by the power dam in Lilla Edet and the so called Vänern regulation, *i.e.* the regulation of the power dam tapping from Lake Vänern, which has been applied since 1937. Already in 1963 Sundborg and Norrman mentioned that

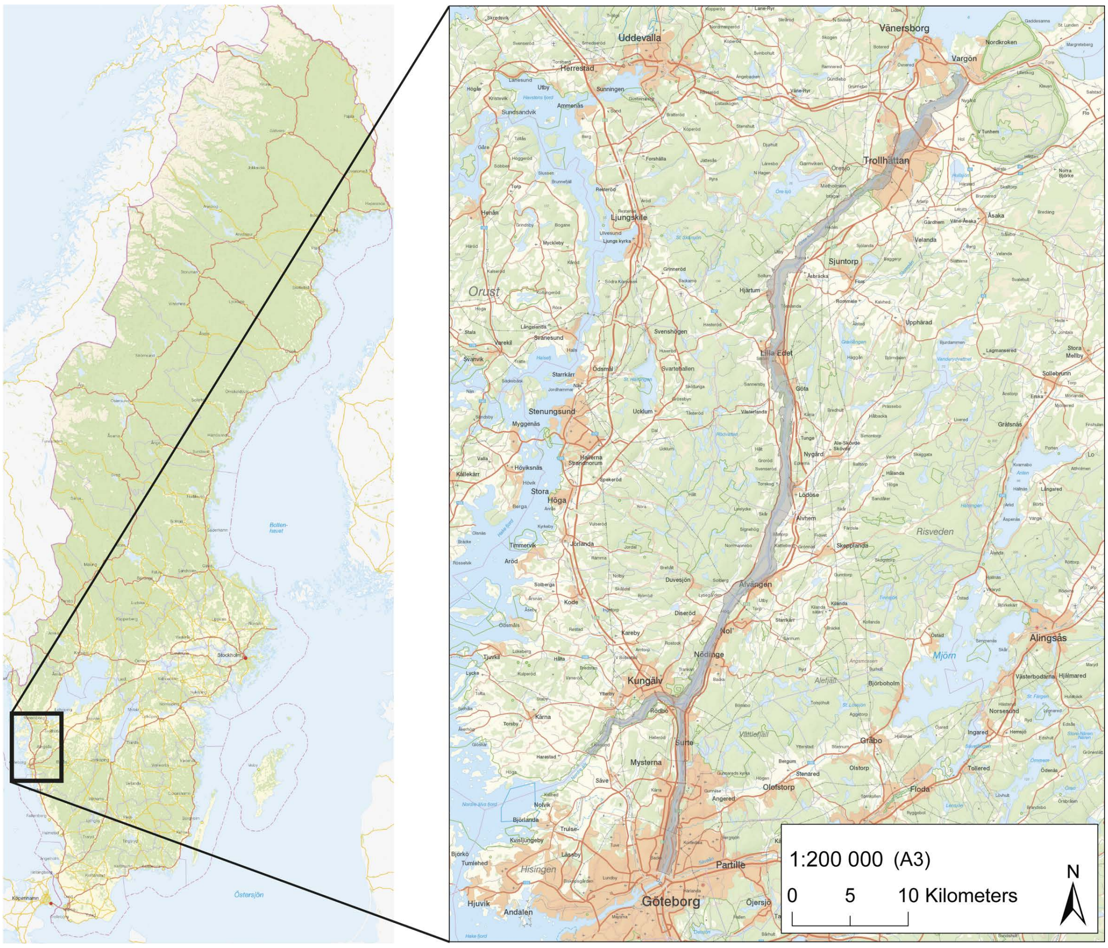

Figure 1. The Göta river valley (study area marked in grey). © SGI, Lantmäteriet, Geodatasamverkan.

the regulation caused increased erosion and frequency of river beachfront landslides [41,43]. Climate change is expected to increase the frequency of extreme flows (high and low) from Lake Vänern further contributing to increased erosion [44,45].

The Göta river valley has a long history of anthropogenic activities such as settlements, shipping, harbours, industry, contaminated soil and infrastructure including large roads and railroads, e.g. [46]. Consequently the consequences of a large landslide can be severe.

2.2. Methodology for Quantitative Landslide Risk Assessment

2.2.1. Landslide Probability

The landslide probability was assessed based on *slopestability* factor estimates along the investigated area. The slope stability was calculated applying an overall security profile in accordance with the national code for practice instructions [47] by Slope/W 2007:7:13 (or later versions) method Morgenstern-Prices with "optimized" sliding surface, or the software GeoSuiteStabilitet 4 (or later versions) method Beast 2003. In all calculations hard crust and half way water filled cracks was assumed. Road and railroad loads were based on TK Geo [48] and building loads were assumed 10 kPa per estate floor. The calculations were done for both drained and undrained analyses, and the lowest resulting safety factor was used. Water levels were set as the lowest allowed level based on tapping and sinking limits of the river system and the average low sea water level as described in more detail in [49]. The slope stability calculations were based on the following information:

- Compilation on geology and stratigraphy in the valley based on recent investigations [50-53].
- GIS based terrain model in SWEREF99TM, RH 2000 [54] based on recent air and sea based laser scanning by Vattenfall ABin 2007, complemented by multibeam echosounding of the river bed within this investigation [55].
- Geotechnical field measurements for in total 240 sections perpendicular to the river. Along each section up to 6 bore holes have been investigated regarding: Total pressure soundings (664), CPT (804), soil-rock soundings (12), impact sounding (21); remoulded

sample (333); vane shear testing (379); piston sampling (291); pore water pressure (557 in 70 stations). In total ca 2500 geotechnical analyses were done, and were complemented with information from previous geotechnical investigations in the area.

- Laboratory investigations of field samples from the investigated sections were done in accordance with SIS-CEN ISO/TS 17892-nr including earth measurements and type of soil estimates (3900), bulk density (3600), water content (3500), cone liquid limit (3100), cone tests undisturbed soils (3000), remoulded soils (2200), CRS (755), direct shear tests (106) and triaxial tests (7).
- Current ground water conditions based on field measurements (34 stations) combined with a compilation of previous investigations [56].
- Current erosion in the river was assessed based on investigations in the area [49].

Based on the information described above the landslide probability factor, P_f, was calculated. P_f was calculated for in total 80 sections in 39 different type areas (based on topography and geological conditions including geometry, undrained shear strength and soil density). The specific conditions for each type area were based on a previous classification by Millet [57]. The landslide-probability factor was calculated by First Order Reliability Method (FORM) [58]. The marginal to slope failure, the so called safety marginal, M, which is the difference between the load capacity and the load, is central in this method. If M > 0 the load capacity is larger than the load effect and for M < 0 the load capacity is less than the load effect. The landslide probability factor is the probability for slope failure, Equation (1):

$$P_f = p\ (M < 0)\,. \qquad (1)$$

The safety marginal, as applied here, was calculated as a function of the safety factor, F, Equation (2):

$$M = \ln F = \ln\left(\eta_{\text{model}}\,Nc/P_d\right). \qquad (2)$$

F was calculated in accordance with Janbu [59] based on the model error, η_{model}, average shear strength along the sliding surface, c, the stabilitynumber, N, and the driving force pressure, P_d. The model error is applied to compensate for the deviation caused by the idealization of the modeled slope [59]. The stability numbers were taken from Janbu [59] and Alén [60]. The driving force pressure (P_d) was calculated by Equation (3):

$$P_d = \gamma \cdot H + q_e - \gamma_w \cdot H_w\,. \qquad (3)$$

where γ is the average pressure caused by the soil layers above the slope foot, H is the vertical distance between the slope crest and foot, q_e is the equivalent surface load behind the slope top, γ_w is the pressure caused by the water in the water course and Hw is the distance between the water level in the water course and the slope foot. Including Equation (2) into Equation (1) results in Equation (4):

$$\begin{aligned} P_f &= p\left(\ln F < 0\right) \\ &= p\left[\left(\ln \eta\text{model} + \ln N + \ln c - \ln P_d\right) < 0\right]. \end{aligned} \qquad (4)$$

Which, when taking into account the variation of data information, can be expressed as Equation (5):

$$P_f = \Phi\left(-\beta\right), \qquad (5)$$

where Φ is the standardized normal distribution and β is the safety index which is calculated based on the average safety factor (μF) and the safety factor variation coefficient (V_F) in accordance with Equation (6):

$$\beta = \mu \ln F/\sigma \ln F \approx \ln\left(\mu F\right)/V_F\,, \qquad (6)$$

where $V_F \approx$ the standard deviation for the safety marginal, σlnF.

The results from the calculations are the landslide probability factor P_f and the safety factor, F. These parameters were used to express the landslide probability in five classes, S1 - S5, in accordance with previous Swedish classification system and previous risk classification system for the Göta älv river system [61] synchronised with Eurocode, *i.e.* S3 corresponds to Eurocode's lowest accepted security level, as described in detail in Göta älvutredningen [41]. The resulting classification system is presented in **Figure 2**.

The probability factors and safety factors from the type sections were then applied on the additionally investigated sections, ca 200, to estimate the landslide probability class for each of those sections based on the estimated slope stability.

To include the potential extension of a landslide, thequick clay distribution in the investigated area was identified by total pressure and CPT as described by Möller and Bergdahl [62] and recently applied by Rankka *et al.* (2004). The Swedish definition of quick clay [42,63], *i.e.* sensitivity (St) > 50 and remoulded shear strength (τR) < 0.4 KPa, was applied.

2.2.2. Consequences

The development of a method for consequence classification has previously been described [46]. The starting point of the consequence analysis was landslide consequence identification, followed by an inventory based on interviews, previous investigations and events. The inventory also included GIS based data on vulnerable elements including: Human life and personal injuries; Property; Potential income losses (industry and other commercial enterprises); Environmentally hazardous activities, *i.e.* elements under the emission register EMIR and Seveso classified elements; Contaminated land areas; Infrastructure of national importance: roads, railroads, seatraffic, heating, electricity, communication (tele, IT) and water supplies and sewage systems; Natural and cultural environments. The results of the inventories of each sec-

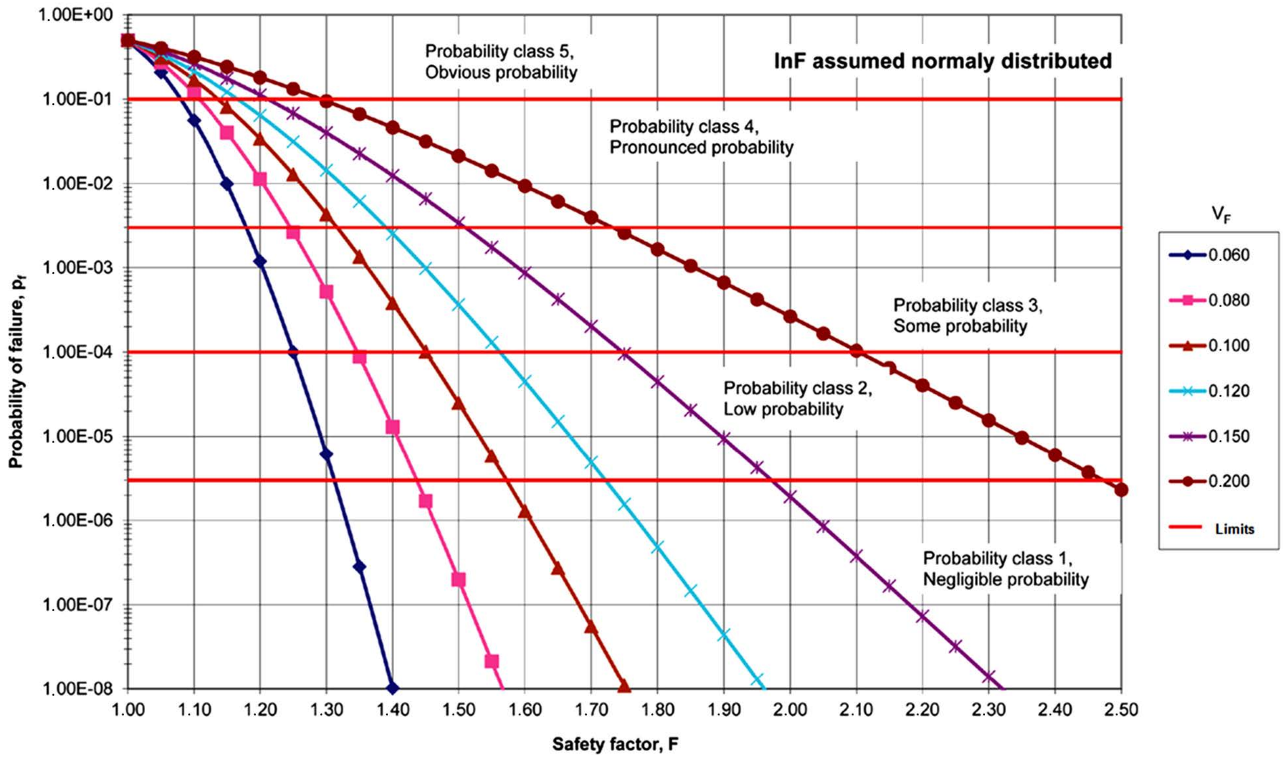

Figure 2. Correlation between probability failure, P_f, and average safety factor, F, for different safety factor variation coefficient, V_F values and the five probability classes, S1 - S5 (modified from Berggren *et al*. [58]).

tor were collected in a GIS raster layer with resolution 100 × 100 m covering the area under investigation [46].

As the consequence in case of an event do not only depend on the number of elements that can be exposed but also the exposure at the time and the sensitivity and adaptive capacity of the system exposed, exposure factors and vulnerability factors were estimated. The exposure factor varies from 0 (no exposure) and 1 (full exposure). The landslide exposure factor for stationary objects such as buildings, roads and railroads, contaminated land and cultural artefacts was set to 1. The exposure factor for human life depend on how people divide their time between work, home, school, etc. at different physical addresses. Human exposure was estimated by applying the results from a time usage investigation for year 2000/01 [64] resulting in an annual average exposure factor of 0.69 for people in their homes. Exposure factors at work and in schools were estimated to an annual average of 0.24 and 0.14 respectively [46].

The vulnerability factor was applied to describe the combined effects of the sensitivity and adaptive capacity. The vulnerability factor for a property can be described as the degree of loss or of damages, and for people the mortality (probability of death) caused by the landslide. The vulnerability factor ranges from 0 (no loss) to 1 (total loss) for primary landslide impacts. The vulnerability factor for human life was determined from previous landslides in Sweden and Norway, *i.e.* the Swedish Natural Hazards Information System [65] and the Norwegian database Skrednett [66] and was expressed as a normal distribution with μ = 0.16 and σ = 0.09 0.16 ± 0.09 [46]. The vulnerability related to a landslide on contaminated land could, for example, be estimated based on the changed risks for human or environment related to the changed exposure of contaminants in the soil both in a short and long time perspective. There is, however, too scarce information for such an estimate. Therefore an alternative approach was applied, in which the impacts were valued using the extra costs related to activities to make the landslide area safe to work on after a landslide event. Similarly, flat values of potential extra costs were-applied for environmentally hazardous activities. For roads, railroads and shipping the impacts on delays, traffic closure and changes of routes were included, as well as reconstruction costs. Costs related to traffic delays and impacts from redirecting road and railroad traffic were estimated through simulations applying different traffic models, *i.e.* Sampers[1] and Eva[2], and the results were implemented in the model applying flat rate values. The vulnerability factor, for a building or any other stationary object, was set to 1 [46].

[1]Sampers is a Swedish National Travel Demand Forecasting Tool (applied by Röcklinger as described in Andersson-Sköld, 2011).
[2]Road Analyses Effects (Effekter vid väganalyser).

The methods for monetary valuation are summarized in **Table 1**. Details can be found in Andersson-Sköld and Falemo [46]. Once the potential consequence had been estimated based on the inventory, exposure and vulnerability factors, *i.e.* Consequence = Inventory*Exposure factor*Vulnerability factor*Monetary value, the consequences were calculated in monetary terms foreach sector and 100 × 100 m grid square GIS of the investigated area. The raster layers were summed up in a GIS raster calculation resulting in total estimated monetary-value of the consequences in each grid square. The raster cells were then summed up in rows perpendicular to the river as the basis for creating consequence class-isolines as shown in **Figure 3**. Five consequence classes were

Table 1. Methods used for socio-economic valuation of potential landslide consequences [46].

Social sector (element at risk)	Valuation method
Human life	Value of a statistical life
Property	Market value
Production losses (industry/commerce)	Average salary per capita Sweden
Environmentally hazardous activities	Extra security and clean-up costs (function of Seveso & EMIR classification)
Contaminated sites	Expected increased cost for remediation and securing the area (function of MIFO classification)
Roads, Railroads, Sea-traffic	Reconstruction cost + value of traffic delays (including increased accidents and maintenance)
Heating and electricity	Reconstruction costs
Water/sewage system	Reconstruction costs
Communication (telephone, IT)	Reconstruction costs
Natural and cultural environments	Only qualitatively

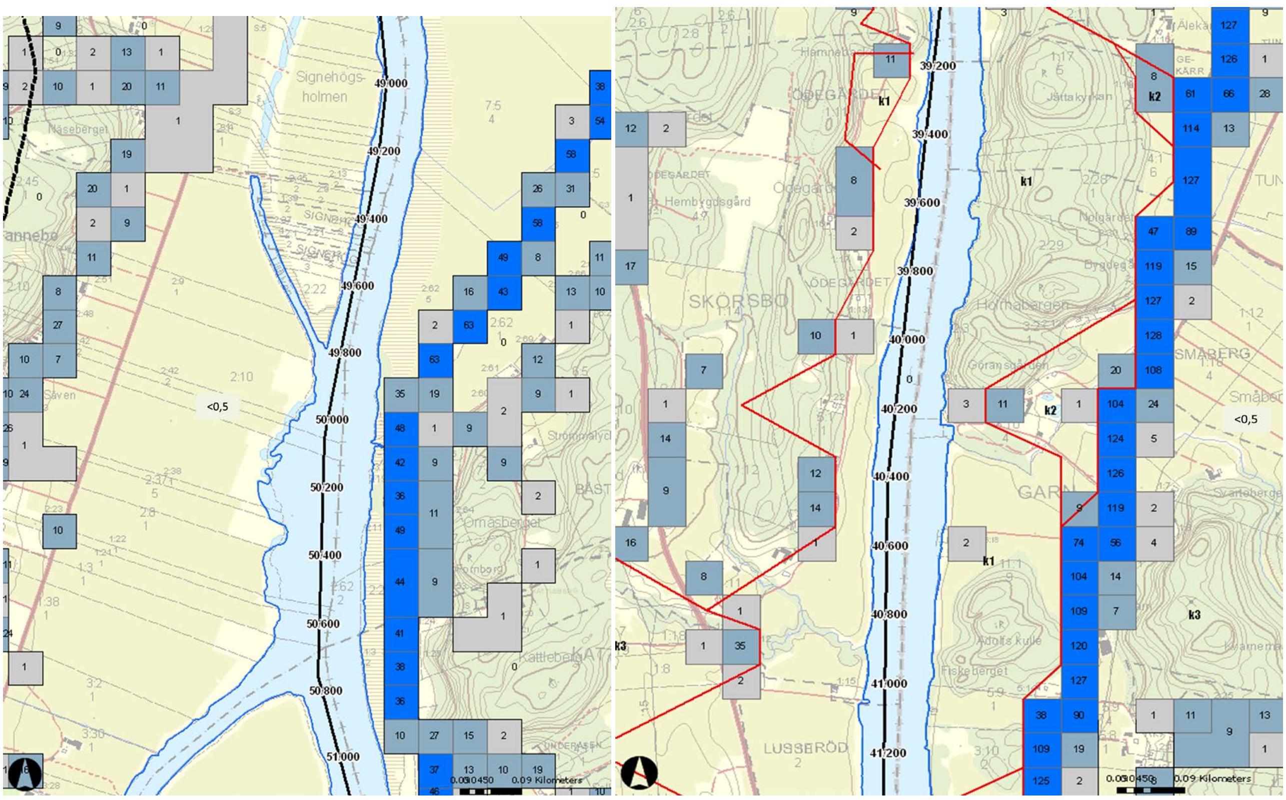

Figure 3. Examples of a resulting consequence map (left) and consequence class iso-lines (right, red lines). The consequences are shown as five classes and the total monetary value within each grid cell: grey (<€0.6 million), blue-grey (€0.6 - 3.5 million), blue (€3.5 - 15 million), purple (€15 - 65 million) and red (>€65 million). © SGI, Lantmäteriet, Geodatasamverkan.

used to map the consequences, K1 - K5 (**Table 2**).

As the monetary valuation is site/context specific the values represented within each of the classes need to be decided among stakeholders/experts with knowledge about the specific investigated area. In this investigation the consequence class values were based on an existing qualitatively based, consequence classification system previously applied in the area [39,61,67]. The resulting landslide consequence map, displaying the resulting consequence classes, illustrates the estimated loss should that entire cell be directly affected by a landslide [46].

2.2.3. Risk Classes and Risk Mapping

The consequence map was then over-layered with the probability map and combined into risk classes. A risk matrix was used to classify consequences and probabilities applying the five classes of each, *i.e.* S1 - S5 and K1 - K5 as summarised in **Table 2**.

The risk is presented as pair of values, *i.e.* the failure probability class and the consequence class, in a matrix system (**Figure 4**). In order to facilitate the readability into a resulting risk map, the resulting risk was divided into three classes, *i.e.* low risk, medium and uncertain risk, and high risk, coloured yellow, orange and red respectively (**Figure 4**).

2.2.4. Time Dependence

The slope stability changes with time due to continuous change in the landslide prerequisites (e.g. erosion and changes in precipitation which alter the river surface level and the pore water pressure). These changes in prerequisites were estimated through scenario based calculations of the safety factor. The scenarios included changes in erosion, water levels and pore-water pressure. Future groundwater scenarios were achieved by combining the current groundwater situation with future climate parameters [68]. The surface water, *i.e.* the river water levels and river water flow for future conditions were based on scenario calculations by SMHI [45] including the expected tapping from Lake Vänern to Göta River [44]. Erosion changes were estimated based on available erosion measurements; water flow scenarios under conditions where current tapping regulation is applied; and for conditions with higher tapping volumes, by applying expert judgments by hydrologists, experts in sedimentology and geotechnical experts. The estimates of the erosion are, consequently, very uncertain and include rough assumptions and rough parameterization.

The results from the erosion calculations shall therefore only be used as indicators of potential magnitudes of changes. In reality the landslide prerequisites may change also due to changes in land use or other man made load changes, such changes have not been taken into account. When assessing the risk over a longer period, such as 100 years, in principle not only the landslide probability but also the time dependence of the consequences shall be included. There are several uncertainties in the changes related to the consequences, including both the social development in the area where the uncertainties of the demographic changes, industrial

Table 2. Landslide probability and consequence class intervals.

Probability/consequence class	1	2	3	4	5
Failure probability	<3.0E−4	3.0E−6 - 1.0E−4	1.0E−4 - 3.0E−3	3.0E−3 - 1.0E−1	>1.0E−1
Socio-economic cost (MSEK)*	<6	6 - 35	35 - 150	150 - 650	>650

*The values within each of the classes need to be decided among the stakeholders/experts for each site specific area.

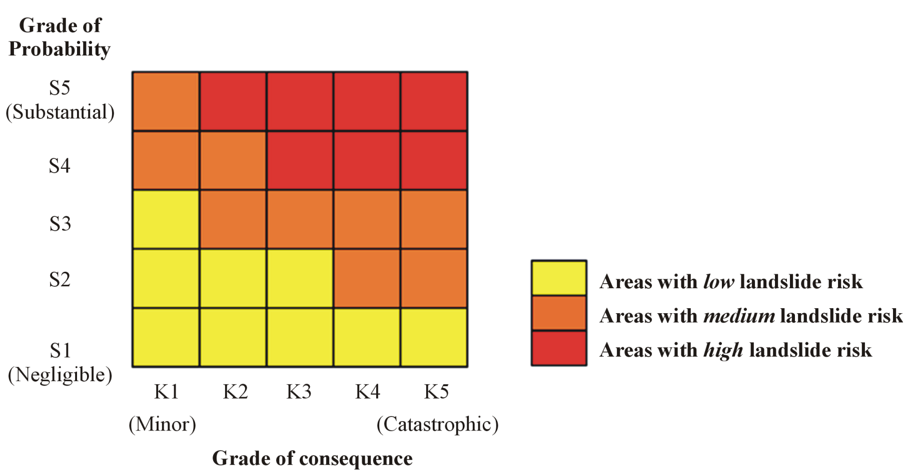

Figure 4. Risk matrix based on landslide probability and consequence classes.

development and socio-economic development are large as are the variations within the investigated region, as are the uncertainties and variations of the current and forthcoming activities and ambition levels regarding physical planning to mitigate the risks etc. Spatial planning in the time perspective of 100 years is expressed in visions rather than in comprehensive plans. Further, the consequence costs estimated in this investigation are not complete due to lack of available knowledge and information, such as costs and vulnerability factors related to human injuries and general knowledge on landslide impacts on the natural environment [46]. Due to the large uncertainties, the time dependence, and consequently any discount rates of consequence costs have not been estimated in this investigation.

3. RESULTS

The major result of the work described here is the development of a methodology that can be applied for landslide risk assessment and mapping anywhere where sufficient GIS data is available. The major steps involved in the methodology are described in **Figure 5**.

The methodology presented in **Figure 5** is generic. For each of the individual steps, e.g. in the landslide probability assessment, several methods can be applied. The basis for the assessment can be based on available information or on new inventories and field measurements. In this paper the results from applying the above described methods in the Göta river valley are presented. The resulting risk map is shown in **Figure 6**. The map is meant to be used as a basis for risk management in the area on local to regional scale. The consequences have a resolution of one hectare and the slope stability analyses were done for sections spaced between 400 and 1500 m, and the map accordingly has to be used for such large scale risk management. For example the high risk class areas (red) need to be investigated in more detail prior to finalizing strategies of physical risk mitigation actions in specific areas. Medium risk class areas (orange) also need to be investigated further. The inclusion of the pair of values can be used to identify whether the more detailed investigations shall be focused on the elements at

Landslide probability

- Compile available information (geotechnical, soil type, hydrological, hydraulic, topography/geometry)
  - Complement with field investigations when needed
- Calculate the slope stability
- Calculate the landslide probability factor, P, the safety factor, F, for type sections
- Apply the resulting probability and safety factors to express the landslide probability in five classes
- Apply the probability factors and safety factors from the type sections on the remaining sections to estimate the landslide probability class for each of those based on the available information on slope stability
- Compile the results in a GIS raster (the resolution depends on the needs for the actual investigation).

Consequence analysis

- Identify potential consequences in case of landslide event
- Make an inventory of elements at risk (the resolution depends on the needs for the actual investigation)
- Estimate the exposure factors (or apply already available ones such as the ones presented in [46].
- Decide on which method to apply for monetary evaluation of each of the sectors/type of elements at risk (methods are summarized in **Table 1** and described in more detail in [46].
- Apply GIS to calculate the monetary value for each of the sectors/type of elements at risk within the investigated area (the resolution depends on the needs for the actual investigation)
- Apply GIS to calculate the total monetary value in each grid cell within the investigated area
- Apply the results to define consequence classes to be applied in the GIS presentation

Risk

- Define risk classes (low, medium, high) based on the consequence and risk classes
- Combine in GIS the resulting landslide probability classes with the resulting consequence calluses into the resulting risk classes in the investigated area (See **Figure 4**).

Figure 5. Stepwise model for GIS based risk map on semi regional scale (river valley scale).

risk, the slope stability assessment, or both.

3.1. Climate Change

The map does not only include information on the current situation but also on expected impacts of climate change. The main impact is due to changes in erosion and thereby the geometric changes of the slopes in and above the river shore line. The erosion depends on the water flow and the water levels, which in turn depend on the maximum tapping and its duration. In the water flow and erosion simulations different future tapping scenarios were included. The maximum tapping is currently regulated to 1030 m^3/s, while in the future either the duration of such tapping will need to increase or the regulation needs to be changed to allow higher maximum tapping. The maximum tapping and potential duration for different potential tapping scenarios is presented in **Table 3**.

The erosion under current conditions and regulations is 0.05 m per year in most parts of the river, with a few exceptions with up to 0.15 m per year.

The erosion under current regulation but in a future climate is expected to be of the same annual mean as today, which is 0.4 to 0.5 m in the northern parts of the river and 1.0 to 1.5 m in the other parts over the next 90 years [49]. For the tapping scenarios 1 - 3, shown in **Table 3**, the erosion will increase, the higher the water flow the higher the erosion. As the most likely tapping will be a mix of the different scenarios the average increase in erosion for the tapping alternatives 1 - 3 is 0.8 to 2 m in the northern parts of the river and up to be-

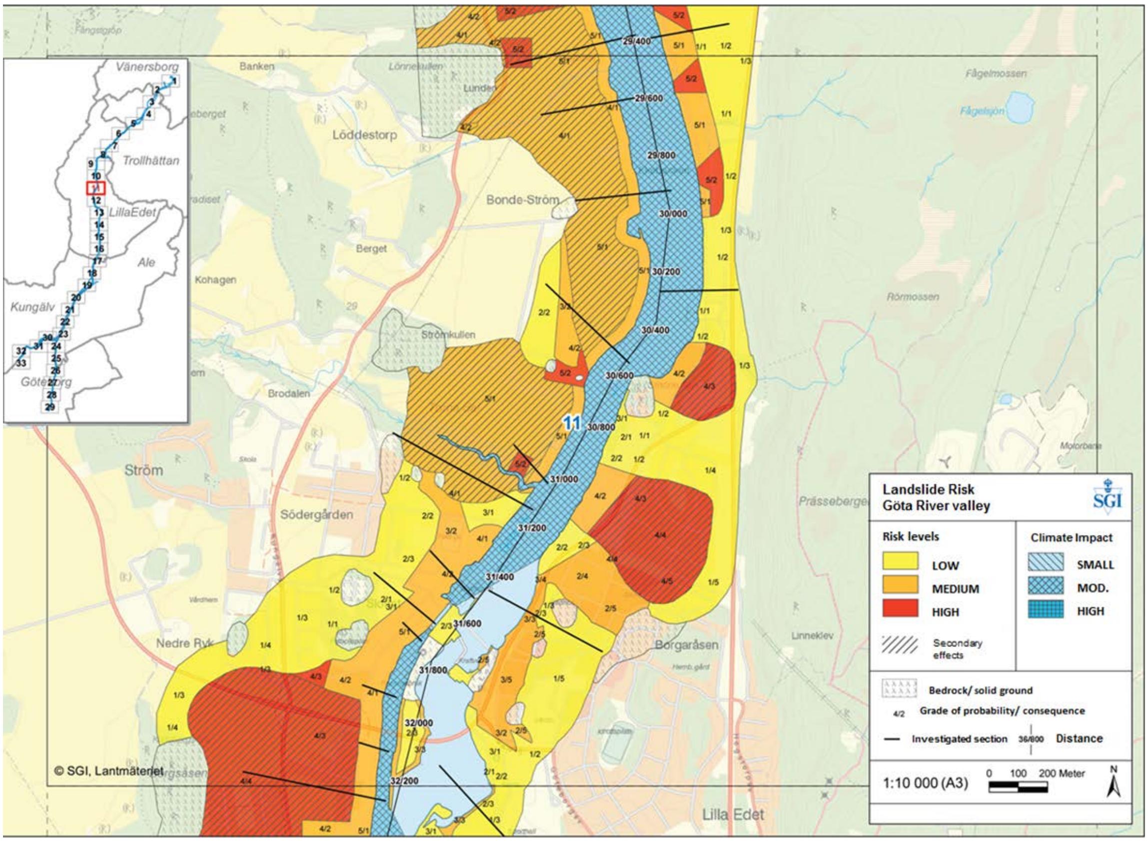

Figure 6. Example of risk map (from GÄU, 2013, part 3 [41]). © SGI, Lantmäteriet, Geodatasamverkan.

Table 3. Maximum tapping and duration under current conditions[3] and simulated for different tapping scenarios [45].

Scenario	Flow rate (m^3/s) (max)	Duration (month)	Flow rate (m^3/s)	Duration (month)	Flow rate (m^3/s) (low)	Duration (month)
0	1030	1	550		170	2
1			780	12		
2	1030	6	780	6		
3	1250	4	780	6	550	2

[3]http://www.lansstyrelsen.se/vastragotaland/SiteCollectionDocuments/Sv/manniska-och-samhalle/krisberedskap/smhi-rapport201085.pdf.

tween 2 - 3 meters in the southern parts of the river the nearest 90 years. The details regarding the erosion estimates are further described in Rydell *et al*. [49].

The impact of erosion on slope stability is estimated to be marginal for areas where the erosion is less than 1m in 100 years. In areas where the erosion is expected to be 1.5 m the slope is expected to move 4 m inland compared to current situation and the safety factor will be reduced by 4%. For the areas and tapping scenarios where the erosion is simulated to be 2 - 3 meters in 100 years, the safety factor will be reduced to 14% on average. In **Figure 7** all sections where the slope stability would be affected by 1 m and 3 m erosion are presented along with the impact on the stability class.

As can be seen from **Figure 7** the impact of erosion is more pronounced in areas where there currently is a low landslide probability compared to where it is high and in general the impact is higher for the higher (3 m) erosion. The potential impact of erosion in the investigated area is shown on the risk map by a raster marking when there may be potential medium or large impacts on the slope stability the nearest 90 years due to climate change and related needs of changed tapping regulations (**Figure 6**).

3.2. Cost Assessment

The result from the risk map was used to estimate thevalue that would be affected in case of a landslide event in the entire area of the investigation (excluding rockyground). The total value was estimated to around €17 billion (150 BSEK). The corresponding value within high risk class areas (red in **Figures 4** and **6**) were calculated to ca € 900 million (8 BSEK) under current conditions. The high risk classed areas (red) will expand due to the shift to higher landslide probability classes in many parts of the investigated area as a consequence of climate change causing higher water flows and thereby increased erosion.

3.3. Mitigation Measures

In areas with high risk (red), risk mitigation measures were suggested by expertise within SGI and a rough cost assessment of the suggested measures was done based on current market prices and experience. The mitigation measures ranged from erosion protection, excavations and embankment to increased maintenance and monitoring and more detailed geotechnical investigations [41]. The estimated cost for suggested measures to decrease the landslide probability by 20% (compared to current landslide probability) in the high risk class areas (red) was €550 - 700 million (5 - 6 BSEK) with operational costs around €10 million (900 MSEK) per year.

The cost hence is less, but in the same range, as the protected value in the protected areas. The difference would be higher if all damages such as personal injuries, personal and municipal administration costs, affection values, cost of stress and sorrow etc. had been accounted for.

3.4. Communication with Stakeholders

The resulting risk map was communicated with the key stake holders in the region such as municipalities

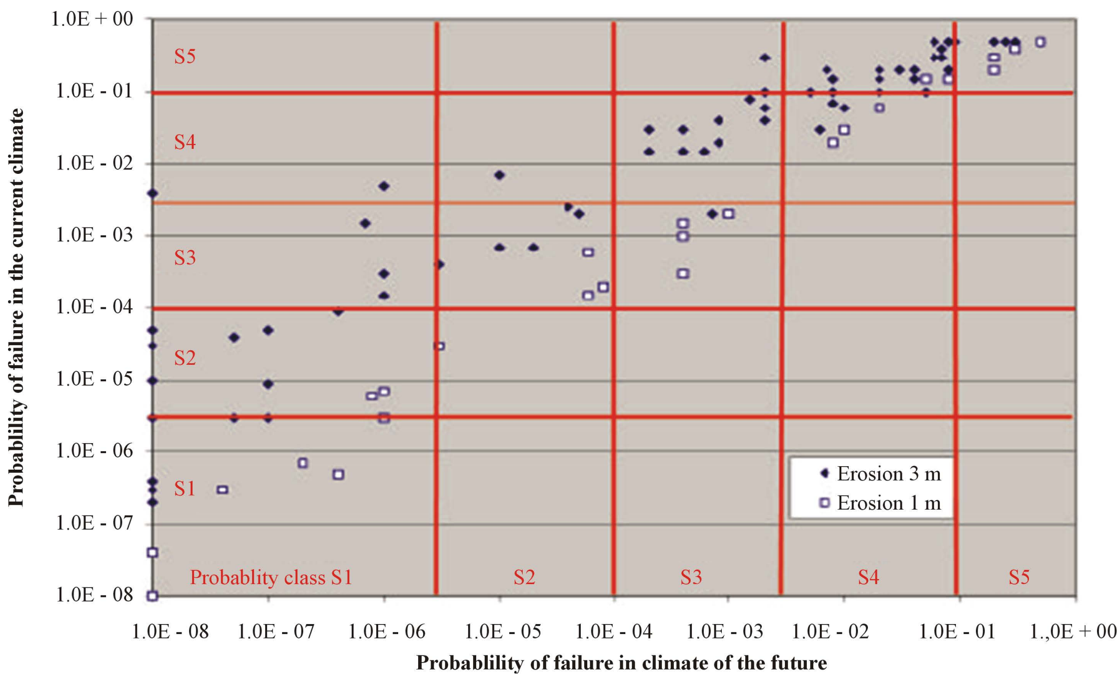

Figure 7. Impact on slope stability class due to increased erosion compared to current conditions.

along the river, the regional road and railroad administration, the county administration board, the water-power industry and the Swedish maritime administration and on national level including for example Swedish Civil Contingencies Agency, the Ministry of the Environment and the Ministry of Health and Social Affairs. Stakeholder communication was initiated by the start of the project and with occasional communication through the course of the project. By the end of the project, the final results were presented and discussed in stakeholder workshops and seminars. The final maps were made available to stakeholders and the public in March 2012. SGI experts had in advance booked meetings with all municipalities along the river to discuss the impacts of the results within each municipality. The maps have been applied as discussion and decision bases in the municipalities, on county and on governmental level to estimate the needs of risk mitigation and to make priorities.

4. DISCUSSION

The main result of the project presented here was a step wise method for landslide risk mapping including landslide probability assessment and monetary valuation of the potential consequences. In the landslide probability assessment applied in the Göta river valley, the up-to-now most thorough field investigation of the area was combined with traditional slope stability analyses, model estimates of current and future erosion and water flows and levels, quick clay mapping and quick modelling to assess the current and future stability and the potential extension of a landslide. The consequence analysis covered more elements at risk than normally included in landslide risk assessments, taking into account both direct and indirect consequences. The reason for such a thorough analysis was the need of more detailed understanding of the risks in the area both under current conditions and taking into account climate change. For efficient mitigation strategies selected areas also need even more detailed investigations and assessments. In such cases the generic method shown in **Figure 5** can, and will be used, but some steps already are described well enough for the purpose. We accordingly recommend the stepwise method to be used in an iterative process focusing on the needs at the moment and aiming to find which areas need further and deeper assessment.

Despite being regarded as a detailed and thorough assessment the results are based on many rough estimates and assumptions, and many uncertainties and unknowns still exist. Among the most important uncertainties are the estimates of current and future erosion and the quick clay distribution which are needed to assess the current and future stability and the potential extension of a landslide. For more accurate assessments several knowledge gaps needs to be filled regarding sediment transport and erosion processes for the different soils in the river. The mapping of quick clay is costly and methods and increased knowledge for faster and cheaper mapping is requested for more thorough estimates.

There are also large uncertainties in the values of the consequences and for some consequences, such as the nature environment, not even the magnitude and whether it is positive or negative impact can be estimated [46]. Of special concern are landslides on contaminated land or enterprises that may cause emissions of contaminants to air, soil and water as there is not enough information to describe the short and long terms impacts, and therefore they cannot even be evaluated. In the same way the impact on biodiversity and various biotopes of a landslide may be both positive and negative and both are in general impossible to quantify with current knowledge and thereby not available for monetary valuation. Human injuries are omitted and costs related to increased administration and soft impacts are also omitted.

The resulting map has been communicated and applied in the landslide risk management by stakeholders and municipalities in the investigated area and despite the uncertainties the resulting map is regarded as very useful and important among the stakeholders. The application of GIS, and that the resulting map is available on the web, is also highly appreciated among the stakeholders. This is in agreement with previous results on the perception of risk mapping and the communication with experts on how to interpret their information [38,69]. The map is useful as it indicates landslide prone areas with high population densities and important vulnerable infrastructure areas that shall be further investigated and regarded for further risk reduction activities. In areas identified as high risk areas, the consequence values are higher, but of the same magnitude as the costs estimated for preventive measures in the same areas. This indicates that preventive measures are beneficial, but also that more detailed site specific analyses are needed prior to identifying and implementing the most cost efficient risk reduction strategies. One of the major reasons for the relative low monetary value in high risk areas are previous landslide prevention measures taken. An example is EKA Nobel where in 1994 land reinforcements for €8 million (70 MSEK) were undertaken. Another example is active land use planning to reduce the vulnerability in the river valley [38]. This is in agreement with an iterative process, *i.e.* that the obvious needs can be treated without as thorough investigation as the one presented here, while in cases where the value of expected losses are close to the costs of risk mitigation measures more detailed analyses are needed. The generic step wise method and GIS based information and data is then easy to apply and combine with the information of the risk map for the larger region, thereby providing information that can be used to develop a more holistic risk management approach and strategy in the entire investigated area.

5. CONCLUSIONS

Risk maps are important tools in communication with stakeholders that may be impacted by potential landslides and/or are responsible for landslide risk management and prevention [38,69].

The level of detail of the risk map must depend on the scale investigated, and to achieve the most cost effective information level, a stepwise method is recommended to be used in an iterative process focusing on the needs at the moment and aiming to find which areas need further and deeper assessment. The method presented here (**Figure 5**) has been found applicable and useful in the preventive work in the investigated area.

There are many uncertainties related to understanding the risks both under current climate conditions and, not least, taking into account climate change.

There is a need for a deeper understanding of the process that may cause serious exposure, and other consequences, to health and environment due to landslides in order to make better quantitative assessments of the consequences.

In general, the understanding of the consequences could be increased if there were more systematically available data with regard to previous events including the number of people exposed and number of injuries in addition to the number of fatalities most commonly presented.

The knowledge on social and individual levels, and the social costs, related to landslides and other severe hazards needs to be better understood.

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