Landslide risks in a changing climate, Nors River pilot study area

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ABSTRACT
The Swedish Geotechnical Institute (SGI) is commissioned by the Swedish government to perform risk assessment for landslides within the national climate change adaptation allowance. Our commission includes mapping the risks in present and future climate conditions.
Making use of material from the previously completed Göta River valley Investigation (GRI), SGI identified and prioritized Swedish watercourses for landslide risk mapping (Bergdahl et al in 2013). The Nors River valley was chosen as a pilot area for the development of a simplified methodology for landslide risk mapping. The investigation along the river is based on the methodology that was developed within the GRI. It aims to provide a sufficient basis for planners in municipalities and county administrative boards in their work with prioritization and preparation of adaptation measures. Methodological development has been carried out in order to reduce the costs of investigation and to simplify the interpretation of the maps, thereby increasing the societal relevance and usability of the results.
The landslide risk analysis along the Nors River valley has resulted in a comprehensive overview of the risk of landslides in the present and future climate, for built-up as well as yet undeveloped land and areas with vital infrastructure. The methodology for risk mapping, that has been developed, is applicable for landslide risk mapping along other streams and river valleys.
The resulting maps are made available in a free GIS Webb application, accustomed to the users of the information.

Keywords: Landslide risk analysis, Climate change, Probability of landslide, Consequenses.

1 INTRODUCTION

Sweden has many areas prone to landslides. Areas along watercourses that flow through loose soil layers are often more vulnerable than others. In such areas the effects of climate change can also become apparent, for example, with increased water flow that causes increased erosion and deterioration of stability in soil layers.
Building further on the Göta River valley Investigation (hereinafter GRI), SGI has developed methods for mapping the risks for landslides. These methods can also be applied for landslide risk mapping in other geographical areas.

The Nors River valley (further referred to by the Swedish name, Norsälven) is the first of a number of subsequent identified river valleys for which the mapping of landslide risk has been planned. Thus Norsälven serves as a pilot area and was presented as a priority in SGI’s budget within the national climate change adaptation allowance. There it is described as, "An investigation of a more comprehensive nature that can be used for planning and decision-making by county administrative boards and municipalities in their adaptation work at regional and local level".
With an overall picture of all areas prone to landslides along the current water course it is possible to make a better substantiated

assessment of which areas require more detailed geotechnical investigations and where geotechnical adaptation measures provide the most public benefit and are most cost-effective. In addition, the municipalities concerned receive a more complete basis for the probability and societal consequences of landslides in already built-up areas, and for the landslide probability in areas where new buildings are planned.

The purpose of landslide risk mapping is to produce a comprehensive map of landslide risks along the current river valley. The map presents the distribution of the risk levels of landslide probability and consequences (in pairs), as well as the impact of climate change on landslide probability in a 100-year perspective. The landslide risk map can be used as a basis for planning and prioritization of climate adaptation measures at the municipal level in their comprehensive plans, and for communication with involved stakeholders.

The methods utilized in the Göta River valley Investigation have been applied as far as possible. However, method development has been necessary to reduce the investigative costs and to simplify the interpretation of the maps without leading to a substantial impairment of the usability. Account has been taken of evaluation and comments that arrived after the Göta River valley Investigation. Among other things, this has served to simplify the results and make them more transparent.

Landslide risk mapping contributes to considerable societal benefits by providing material to:

- avoid/mitigate the consequences of landslides,
- reduce the likelihood of landslides,
- support the national environmental quality objectives good built environment (and good non-toxic environment), and
- provide input to planning for adaptation.

1.1 Scope and limitations

The investigation of Norsälven extends from the Lake Lower Fryken outlet in Kil municipality to Norsälven’s estuary in Lake Vänern in the Karlstad municipality, see Figure 1. In total, this means a distance of about 30 km, equivalent to 60 km shoreline. The investigated area's width is limited to approximately 600 metres from the shoreline, in some cases a shorter distance when delimitation against solid ground could be made. The area has been divided into sections South, Middle and North, see Figure 1. The sub-division is made primarily on the basis of diverse geological conditions but also for practical reasons, as these sections are divided by two hydropower plants at Frykfors and Edsvalla. Investigation of landslide risks in tributaries or deep valleys that lie within the area of investigation has not been done explicitly, but with assessment based on the results of the calculations along the river.

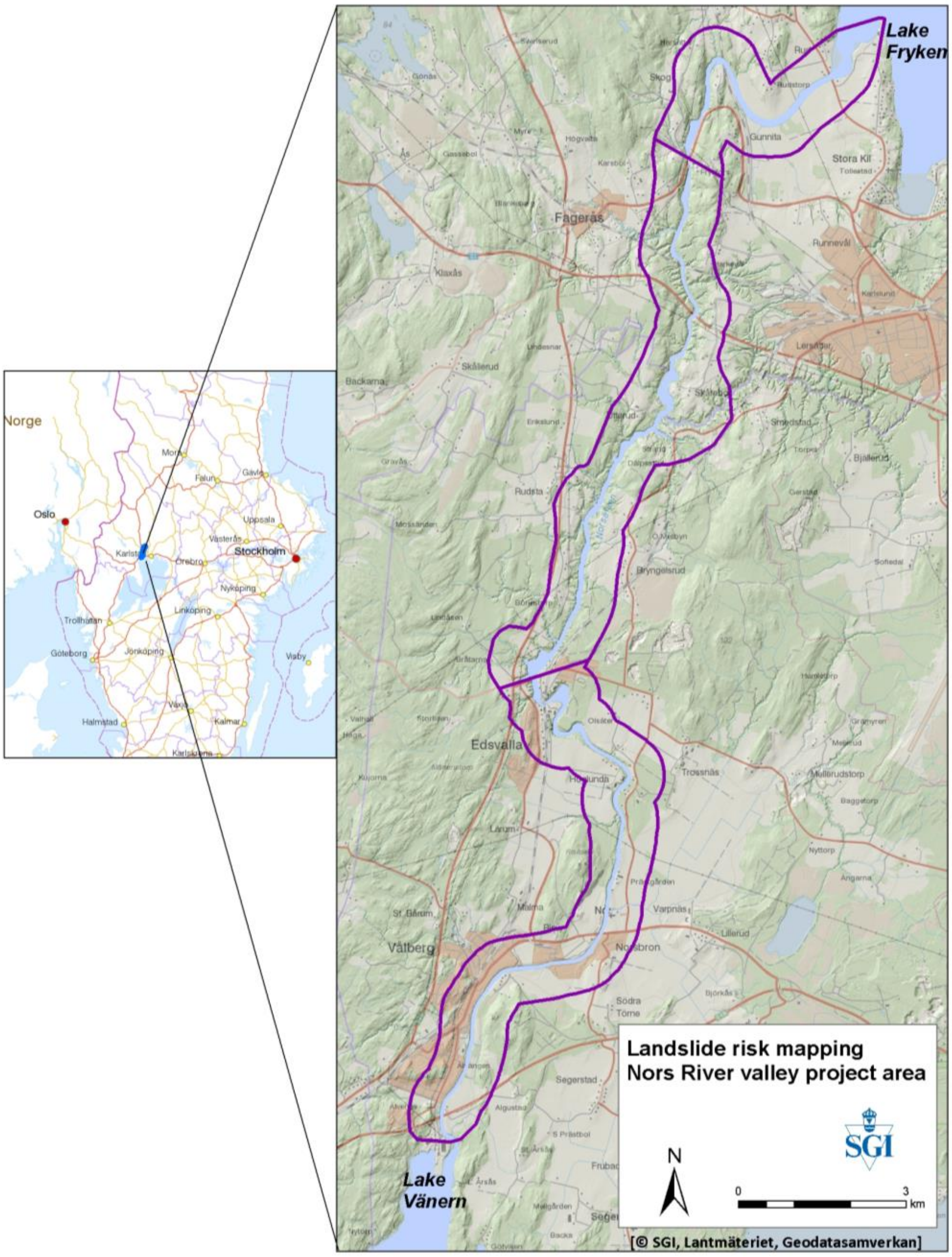

Figure 1 The Nors River pilot study area.

2 PROBABILITY, CONSEQUENCES, AND RISK

2.1 Probability of landslide

In order to obtain as good a description of reality as possible, the traditional calculation of slope safety factors have been complemented by an assessment of the probability of landslides, taking into account the uncertainty that exists in the input parameters. Stability is analysed using parameters which is given a variation that describes their uncertainty. The variation is determined in each case by using experience from similar areas as well as with statistics from surveys and other investigations. Some parameters change over time, and/or as a result of climate change, which means that the calculations must be made both for the current and future situations. The probability has then been calculated using point estimate method, PEM.

The probability of landslides has been divided into five classes, S1-S5, see table 1. The boundaries between the different

probability classes have been based on European and Swedish standards commonly used for design of buildings. Classes have been selected so that probability class S5 means poorer conditions than the worst class that may be accepted for temporary structures, while probability class S1 means better stability than the requirements for common buildings (Berggren et al, 2011, Göta River valley Investigation sub-report 28). The probability in areas between the calculated sections has been estimated based on their geotechnical and geometric conditions in relation to the conditions and results in the calculated sections.
The produced probability map can be used as a guide to show where geotechnical conditions in particular should be taken into account in urban planning.

Table 1 Classification of probability of landslides.

Proba-bility class	Landslide proba-bility	Relative failure probability (Pf)
S1	Negligible	$P_f < 3{\cdot}10^{-6}$
S2	Low	$3{\cdot}10^{-6} \le P_f < 1{\cdot}10^{-4}$
S3	Some	$1{\cdot}10^{-4} \le P_f < 3{\cdot}10^{-3}$
S4	Distinct	$3{\cdot}10^{-3} \le P_f < 1{\cdot}10^{-1}$
S5	Definite	$P_f \ge 1{\cdot}10^{-1}$

2.2 Consequences of landslide

In parallel with the calculation of the probability of landslides, the consequences of landslides along the river have also been assessed. An exhaustive description, and, above all, economic valuation of all possible consequences has not been carried out. The consequences for the buildings and the transport routes in the area have been valued on the basis of four quality criteria; life, environment, economy and social importance. Landslides in the river valley may affect many people and important social functions.
A landslide also means suffering, sorrow or discomfort for many people and thus the overall consequence of a landslide can include various implications for which it is difficult to make a systematic valuation.
Possible impact of a changing climate on the consequences has not been assessed since such information so far has been unavailable. However, according to the national comprehensive planning code, planning decisions undertaken by the municipalities are assumed to take into account the existing conditions as well as conditions in a changing climate.
The consequences have been divided into five consequence classes, K1-K5. In the combination of data with various consequences the greatest value within each grid square has determined the consequence class. This ties in with classification from previous landslide risk mapping and corresponds to a gradual increase in the implications of classes, see table 2.

2.3 Classification of landslide risk

The descriptions above imply that all parts in the investigation area are assigned a probability class and a consequence class. The combinations of these two classes make pairs of values that describe a risk class. This classification can also be displayed in a matrix to show how various risk classes relate to one another, see Figure 2.

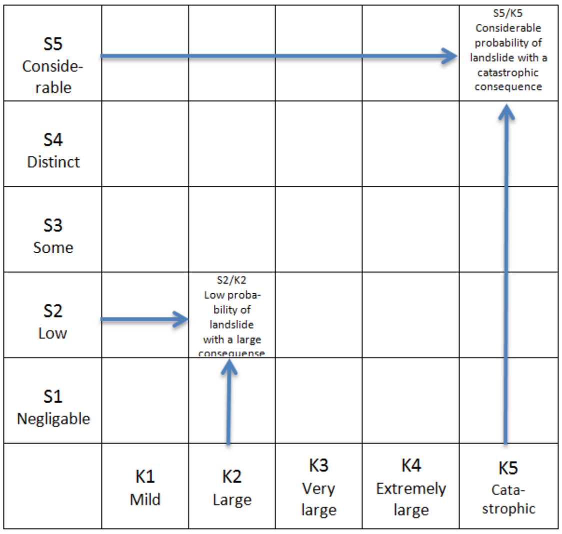

Figure 2 Matrix of risk classes

2.4 Landslide risk levels

In order to simplify the risk assessment the risk categories developed have been grouped into three risk levels consisting of a number of classes that correspond to a similar landslide risk, see Figure 3.

Table 2 Classification of consequences of landslides

Consequence class	Consequences of landslides	Description of Consequences
K1	Mild	No persons are injured or killed. No environmentally hazardous activity/enterprises affected and little environmental risk. Small economic losses. Loss of social function with very little social significance. Other/Minor roads (minor road, tractor road, footpath, running tracks, hiking trail, cable car, ferry route)
K2	Large	A few people are injured or killed. No environmentally hazardous activities/enterprises affected and medium environmental risk. Medium-sized economic losses. Loss of social function with low social significance. Public road class III (width < 5 m); Drive/neighbourhood road.
K3	Very large	Number of wounded or dead persons that corresponds to the number of people in a smaller dwelling with several homes. Environmentally hazardous activities suffer with serious consequences for the environment. Large economic losses. Loss of important social function. Public roads class II (width 5-7 m); Thoroughfare; Road under construction
K4	Extremely large	Number of wounded or dead people that corresponds to the number of people at a larger school, apartment buildings or major railway station. Environmentally hazardous activity involving extremely serious consequences for the environment. Extremely large financial losses. Loss of important social function. Public road separate carriageways; Public road in (width > 7 m)
K5	Catastrophic	Number of wounded or dead people that corresponds to the number of people in an indoor arena (thousands people, high density). Environmentally hazardous activity involving catastrophic consequences for the environment. Catastrophically large economic losses that distinguishes itself from most of the economic losses. Loss of very important social function. All railways; Highways

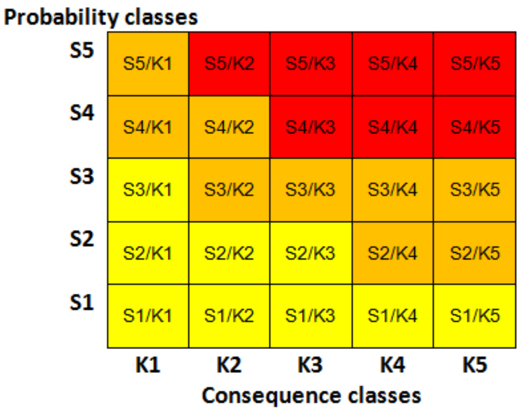

Figure 3 Matrix of risk levels

Risk levels are expressed as low, medium and high risk. See Figure 5 for a more detailed description of the different risk levels.

2.5 Risk of progressive landslides and secondary effects

In areas with highly sensitive clay/quick clay, progressive landslides may occur where large areas may suffer from continuous land sliding. Such an event means that secondary consequences in addition to the losses and damages to the land may occur. Examples of secondary effects that may occur are impoundments of the river (and its tributaries) and tidal waves of different magnitudes depending on the volume of the sliding mass. These secondary consequences may, if the affected area is sufficiently large, exceed the primary consequences in the area. The secondary consequences cannot be predicted with enough certainty, and therefore have not been addressed in the inquiry.

2.6 Climate impact

Anticipated climate change involves increased future flows in the river, implying increased erosion on the river banks and bed, as well as higher groundwater and pore water pressure. This has an impact on the probability of landslides because of slope geometry change within large parts of the area of investigation. This climate impact is expressed in three classes: low, moderate and high impact. Climate impacts are reported on the landslide risk maps with different dashed patterns in the river area.

Depending on the class of an area, climate change will result in a probability class increase of one to two levels within some sections along the river. In areas with the highest probability class (S5), even a small influence caused by climate change can mean that landslides may occur and thus a high impact level.

2.7 Digital data

In the investigation a large number of external supporting data have been collected and used. Multiple datasets have been acquired via SGI's participation in the Swedish “Geodatasamverkan” or geodata collaboration, for example, concerning different maps, charts and the national elevation database. During the investigation a lot of new data and results have also been produced. When gathering background material, the digital material has been added in databases. The investigation has sought to collect data in a GIS format. The datasets have been managed in a GIS environment where the reference systems, SWEREF99TM in plan, and RH2000 in height has been used. The work has used ESRI ArcGIS, QGIS, and Web-based GIS applications.

Final results in the form of landslide risk classes, probability and consequence classes are made available in a Web-based GIS application that is open to external users. In the map other selected supporting data will also be shown which may be useful when using the survey's results. Supporting external data appears in the so-called WMS version from the data producer.

Figure 4 shows an excerpt from the Web-map application developed for presenting the results from the investigation.

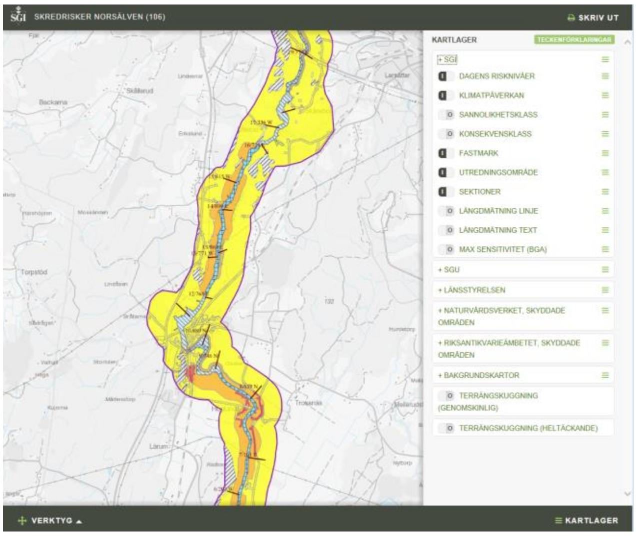

Figure 4 Excerpt from the Web-map application.

3 LANDSLIDE RISK IN NORS RIVER VALLEY

3.1 Summary of the results

In broad terms, the investigation shows that the probability of landslides along Norsälven is definite in much of the South section and parts of the Middle section. In the North section the probability is distinct all along the south western bank of the river, but otherwise mainly low.

The impact is the greatest in the South section where communities of Vålberg and Edsvalla are located, as well as by the major road and rail facilities that exist within the whole area of investigation.

Areas of high landslide risk are relatively limited along the river (2% of the assessed surface). These areas are found primarily closest to the river. Along the greater part of the river valley a medium risk level is assessed and usually closest to the river banks (13% of the assessed surface). The main part of the investigation area has a low level of risk (86% of the assessed surface).

The sensitivity to a future climate change is highest in the South section, the lower part of the Middle section and a limited part of the North section, mainly due to the high probability of landslides already for present conditions.

3.2 Presentation of results in maps

The investigation's results are reported in three different map series at the scale 1:15 000 (A4). The results are separated into probability maps, consequences maps and combined landslide risk maps.

In Figure 5 the different symbols are described as well as designations appearing in the legend on the risk maps. The cumulative risk (of probability and consequence) is reported at three levels: Low, Medium and High risk level.

3.3 Using the maps

The overall consistency of a landslide depends on the size of the landslide. The most common scenario is that a landslide begins at the riverside and evolves backward to different degrees depending on soil mass properties and the topography of the area. Where quick clay is present the landslide could be extensive. The aggregated consequences are not shown in the maps of consequences, but must be assessed in each individual case.

Risk level

Area with **LOW** landslide risk. No special investigation is required for existing buildings and facilities. New buildings and developments require stability investigation.

Area with **MEDIUM** landslide risk. Existing buildings and structures should be checked by detailed stability studies. New buildings and developments require stability investigation and possibly action is to be taken.

Area with **HIGH** landslide risk. Need of action for existing buildings and structures should be clarified with detailed stability study. New constructions require detailed investigation of stability and likely measures to improve stability conditions.

Climate impact

LOW sensitivity to climatic influences. Climate change generally implicates no change in probability class.

MODERATE sensitivity to climatic influences. Climate change causes the probability class to increase by one level in the relevant sections along the river.

HIGH sensitivity to climatic influences. Climate change causes the probability class to increase by one to two levels in the relevant sections along the river.

Figure 5 Explanation of the legend on landslide risk maps.

Figure 6 shows mapped historical landslide areas for part of the South section with various map backgrounds. This is given as an example of how to assess probable landslide extent and get a rough idea of the size of the impact.

4 REDUCING LANDSLIDE RISK

Landslide prevention measures are an important part of the work with urban planning, both in view of the current climate and with regard to climate change over the longer term. The landslide risk maps give a

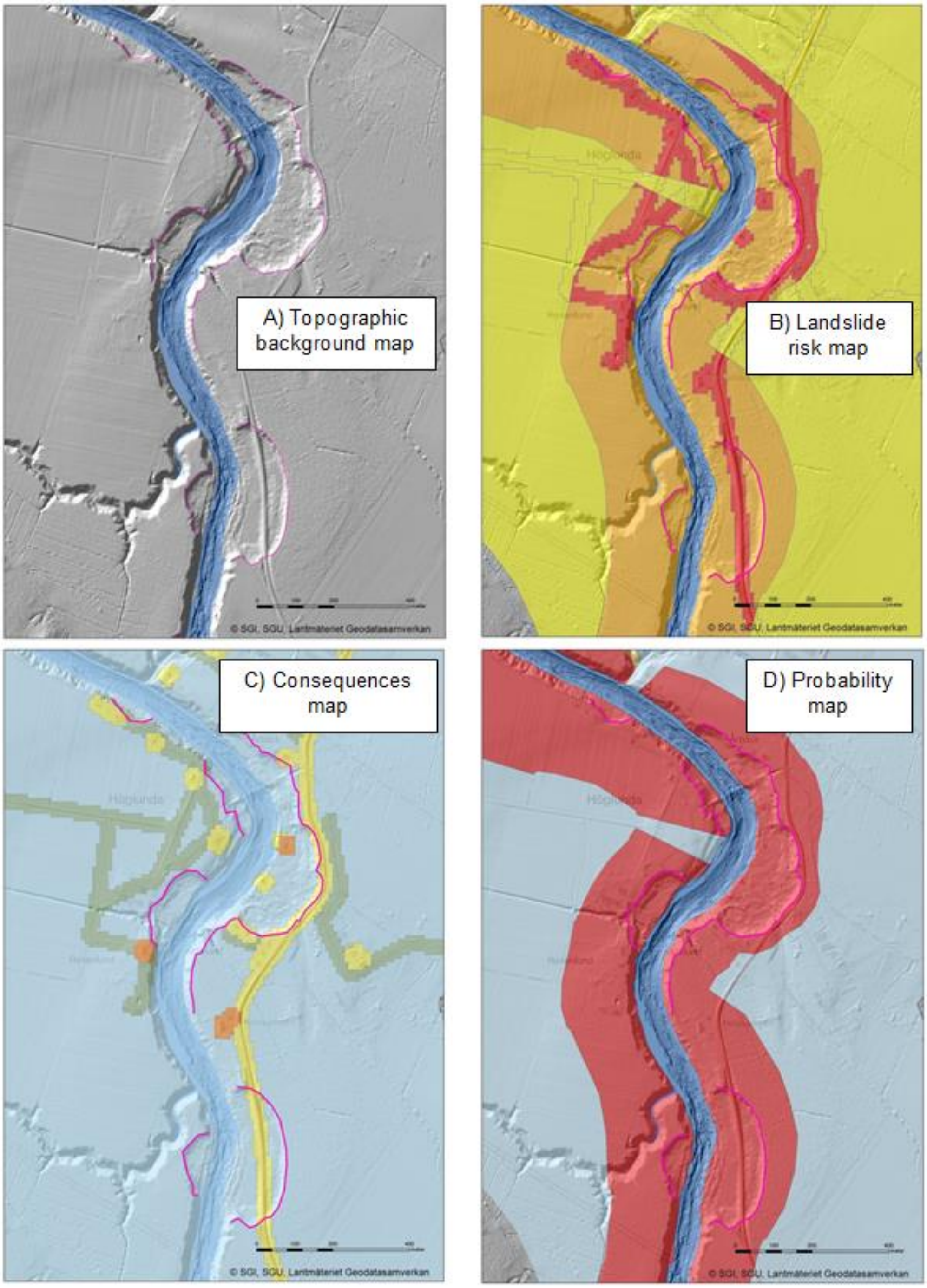

Figure 6 Views of previous landslide expanses (pink line) within the territory of the South section in various maps. The sizes of the landslides are approximately 200 m long and 100 m deep on the western side, and 350 m long and 150 m deep on the eastern side (the southern landslide scar). © SGI, SGU, LM, Geodatasamverkan. A) The topography is from the National elevation-data and bathymetric data, B) Risk levels as Low (yellow), Medium (orange) and High (red), C) Consequence class K2 (green), K3 (yellow), K4 (orange), D) Landslide probability class S5 (red).

picture of where there are sensitive areas to pursue and investigate in more detail by clarifying the geotechnical conditions, as well as the consequences that could arise from a landslide. To do this, one must take account of a "probable" landslide extent because the total consequence of a landslide is the sum of the effects within the probable landslide extent. The maps also provide an indication of the areas likely to be affected most in a changed climate.

The results of this investigation can be used to influence the siting and construction of new buildings and activities so that landslide risks can be prevented. To reduce the risk of landslides along the river, measures to reduce the probability and/or consequences could be taken. Measures to reduce the probability of landslide are usually physical in the form of excavations, supporting fill or erosion control. Measures to reduce consequences can be, for example, moving buildings and facilities. Along Norsälven several examples are found where redemption of property has been used as an action for reducing landslide risks.

Below are summary recommendations for the investigation area along Norsälven:

- Identified areas of high landslide risk levels should be further investigated for possible actions.
- A zone with restrictions, as established by the municipality of Karlstad, may be a good way to verify activities that may affect the stability. It may be relevant to review the extent of the zone.
- When investigating possible actions, it is important to take into account the presence of quick clay, which affects the extension of possible landslides.
- A review of existing erosion control should be carried out within the South sector, with regard to the maintenance and additional measures.

4.1 Urban planning and building

The landslide risk map has a resolution that is suitable for comprehensive planning. It is possible and recommended to consider this in connection with other risk areas for natural disasters, such as flood risks.

For detailed planning and building permits, more detailed geotechnical investigations should be made, taking into account the buildings and the facilities that the planning/building permit will allow. This action should be taken to prevent an increase in the probability of landslides within the current area.

It is also important to consider that the level of risk may be increased as consequences increase, that is to say, if the land is exploited with buildings or facilities. Other changes in land use may also play a role in the landslide risk level. For example, the neglected maintenance of land drainage due to land use change could lead to a build-up of water pressure in the ground that may increase the likelihood of landslides.

4.2 Detailed investigations

Geotechnical stability investigations tend to be made with multi-stage increasing levels of detail. In Swedish documents such as IEG 4:2010 and Skredkommissionen report 3: 95 for planning and IEG 6:2008, rev 1 for design and construction, information is found about regulations and recommendations for geotechnical stability investigations according to Swedish standards.

4.3 Climate adaptation measures

Before making decisions on risk-mitigation measures, a quantitative cost-benefit analysis should be done where the cost of a measure is weighed against the benefits. Then the probability of landslides and the consequences can be studied in more detail for a defined area to decide if the action should aim to reduce the probability of landslide and/or the consequences. Physical measures to reduce the probability of landslide in the form of excavation, supporting fill, erosion control, soil reinforcement, etc. are often costly. Options that reduce the consequences can sometimes be more effective. Such alternatives may include the redemption of property / demolition of building on a property or restrictions in the use of land.

Preventive measures against natural disasters can sometimes counteract each other's' purposes. For example, a flood prevention dike causes a load of soil layers that may impair the stability of the area. It is therefore preferable to coordinate different kind of climate adaptation measures.

5 CONCLUSIONS

In comparison with the GRI the pilot study for Norsälven has resulted in a modified methodology which enables risk analysis at lower cost and yet sufficient accuracy. It gives a comprehensive overview of the risk of landslides in the present and future climate, for built-up as well as yet undeveloped land, and areas with vital infrastructure. The methodology is also applicable for other river valleys, although further adjustments may be needed due to geological and other differences. This will be tested for the next river in line, Säveån in Southwest Sweden, and for the river Ångermanälven representing the Northern parts of Sweden.

6 AKNOWLEDGEMENT

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The study is presented in full in the SGI report "Landslide risks in a changing climate – The Nors river valley, SGI Publication No. 18-1, 18-1E (English version), 18-2, 18-3 and 18-4, 2015.

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