Mass movements as contamination carriers in surface water systems – Swedish experiences and risks

Maria Åkesson

Examensarbete i geologi vid Lunds Universitet - Kvartärgeologi, no. 253
(45 hskp/ECTS)

Institutionen för geo- och ekosystemvetenskaper
Enheten för geologi
Lunds universitet
2010

Mass movements as contamination carriers in surface water systems

- Swedish experiences and risks

Master Thesis

Maria Åkesson

Department of Earth and Ecosystem Sciences
Division of Geology
Lund University

2010

Contents

Cover: Section of the Göta Älv river valley; the most mass movement-affected SWS in Sweden. Photo by Gunnel Göransson (2008).

Mass movements as contamination carriers in surface water systems
- Swedish experiences and risks

MARIA ÅKESSON

Åkesson, M., 2010: Mass movements as contamination carriers in surface water systems - Swedish experiences and risks. *Examensarbeten i geologi vid Lunds universitet*, No. 253, 46 pp. 45 points.

Abstract:
Recent studies indicate a widespread but largely overlooked hazard of contaminant mobilisation and transport in connection to mass movement activity into surface water systems in Sweden. Concerns are exacerbated by predicted effects of climate change, which suggest national increases in rates of precipitation, pore water pressures, run-off, erosion and mass movement occurrence. In this study, the national scope, character and potential of the proposed hazard and associated risks are assessed based on a review of approximately 400 mass movement events. Hazard analyses of three risk areas along rivers Viskan, Klarälven and Ångermanälven are also presented.

It is concluded that parts of most major Swedish river systems, as well the lakes and coastal areas into which these debouch, are already likely to be at risk of the proposed hazard. Within the three studied risk areas, 102 environmentally hazardous facilities and/or sites of established or suspected soil contamination were found to lie within areas at risk of slope failure. The variation in character of historical mass movement activity on the one hand, and types of environmentally hazardous facilities/soil contamination on the other, indicate that the scope and nature of the hazard in between as well as within any given risk area varies with time and location according to concurrent geologic, climatic and biologic conditions, and, according to extent and type of human activity.

It is shown that materials set into suspension upon slope failure into running waters may stay in suspension for months, being carried upstream for several kilometres, and downstream for several tens of kilometres. Displaced materials are further demonstrated to be able to cause enhanced mobilisation of materials through surging, and, through upstream inundation and long-term/permanent alterations of downstream flow- and erosion patterns brought about by damming. Mass movements into surface water systems hence appear as an efficient potential means of widespread, short- and long-term contaminant transport throughout much of Sweden.

For the future, hazard awareness raising and clarification of responsibilities amongst involved actors are considered the main and most important tasks. The need for more interdisciplinary collaboration, research and exchange of experiences - nationally and internationally - is also stressed.

Keywords: mass movements, surface water systems, contaminant mobilisation, contaminant transport, natural hazard, Viskan, Klarälven, Ångermanälven

Maria Åkesson, Department of Earth and Ecosystem Sciences, Division of Geology, Lund University, Sölvegatan 12, 223 62 Lund, Sweden. E-mail: maria.akesson.303@student.lu.se

Massrörelser som föroreningsspridare i ytvattensystem
- svenska erfarenheter och risker

MARIA ÅKESSON

Åkesson, M., 2010: Mass movements as contamination carriers in surface water systems - Swedish experiences and risks. *Examensarbeten i geologi vid Lunds universitet*, Nr. 253, 46 sid. 45 poäng.

Sammanfattning:

Studier har nyligen antytt att det över stora delar av Sverige skulle kunna föreligga risk för föroreningsspridning i samband med massrörelser intill ytvatten. Då framtida klimatförändringar förväntas öka såväl mängd som intensitet av nederbörd, avrinning, erosion och därmed även massrörelser över stora delar av landet, framstår farhågorna som än mer välgrundade och oroväckande. I den här studien analyseras den nationella omfattningen såväl som den fysiska karaktären och potentialen av den föreslagna faran genom en granskning av knappt 400 dokumenterade massrörelser. Detaljstudier av tre riskområden längs med Viskan, Klarälven och Ångermanälven presenteras också.

Det konstateras att det kring de flesta stora svenska ytvattensystem sannolikt redan föreligger risk för föroreningsspridning i samband med massrörelser. Inom de tre detaljstuderade områdena identifieras 102 miljöfarliga anläggningar och/eller konstaterat eller misstänkt förorenade områden inom direkt instabila avlagringar. Variationen i historisk massrörelseaktivitet och typ av miljöfarlig/förorenande verksamhet tyder på att omfattningen och karaktären av faran och riskerna mellan och inom varje enskilt område varierar över tid och rum i enlighet med geologiska, klimatologiska och biologiska förhållanden, och med omfattning och typ av mänsklig verksamhet.

Det konstateras att material som suspenderas i samband med en massrörelse intill rinnande vatten kan förbli i suspension i månader, transporteras uppströms i flertalet kilometer och nedströms i tiotals kilometer. Utskredade massor förevisas även kunna orsaka mobilisering och vidare transport av ytterligare material såväl upp- som nedströms genom svallvågor, dämningseffekter och efterföljande förändringar i strömnings- och erosionsmönster. Massrörelser intill rinnande vatten, sjöar och hav över stora delar av landet förefaller således kunna sprida betydande mängder föroreningar över stora områden, över både korta och långa tidsskalor.

Att öka medvetenheten och kunskapen om faran och riskerna bland berörda auktoriteter, samt att tydliggöra påföljande ansvarsfördelning, anses vara de absolut viktigaste uppgifterna för framtida riskhantering och -reduktion. Det finns även ett stort behov av mer tvärvetenskapligt samarbete, forskning och utbyte av erfarenheter, såväl nationellt som internationellt.

Nyckelord: massrörelser, skred, ytvattensystem, föroreningsspridning, naturkatastrof, Viskan, Klarälven, Ångermanälven

Maria Åkesson, Institutionen för geo- och ekosystemvetenskaper, Enheten för geologi, Lunds Universitet, Sölvegatan 12, 223 62 Lund, Sverige. E-post: maria.akesson.303@student.lu.se

1. Introduction

Mass movements are some of the most widespread, most damaging natural hazards on Earth. In a recent World Bank report, Dilley et al. (2005) estimates that a global land area of about 3.7 million km^2 is repeatedly subject to mass wasting processes. Accordingly, about 300 million people worldwide are continuously exposed to and at risk of related hazards. Every year, millions of people are affected, thousands killed and/or injured and economic losses are to be counted in billions of dollars (Centre for Research on the Epidemiology of Disasters [CRED], 2008). The socioeconomic as well as the environmental consequences and risks are no doubt major. Nevertheless, it is often suggested that the full effects of mass movements tend to be underestimated. This since they are often accounted for as the consequences of other natural hazards (e.g. earthquakes, floods responsible for the triggering of the mass movements) and thus merged with those when assessed (Kjekstad & Highland, 2009). Moreover, whereas much political and scientific attention is always given the more direct consequences and their costs (fatalities, injuries and damage to the built environment), less tends to be given the more indirect or secondary consequences and costs; that is those concerning the potentially more profound and long-lasting effects on the environment and the natural resources we and our societies have come to rely upon for survival.

With respect to mass movements, one of the most affected natural resources is the most fundamental of them all, namely water. The physical characteristics of streams, lakes and ocean coasts around the globe are repeatedly – in some cases as good as continuously – affected by the geological, hydrological, chemical and biological rearrangements that these processes and resultant sediment pulses impose on them. Hence, the ecological status of numerous surface water systems (SWS), also serving as critical water supplies for millions of people worldwide, are inevitably also affected. However natural the process, risks are certainly major and especially so in areas in which the soils at risk of failure have suffered pollution. Unfortunately, mass movements as potential contamination carriers in SWS appear a largely unrecognised and overlooked hazard (Göransson et al., 2009). Documentation and knowledge of key factors, processes and their respective interactions is lacking and so proper risk assessment hindered. Concerns ought to be global, especially since human as well as environmental vulnerability and risks in connection to mass wasting processes are bound to continue to increase with escalating population pressures and predicted effects of climate change.

1.1. Background, motivation and aim

Between 1999 and 2005, the Swedish Parliament adopted sixteen environmental quality objectives. The objectives define long-term targets for the state of various environmental compartments in order to accomplish environmental sustainability, what ought to be done in order for the respective objectives to be met, and also which governmental authorities that are responsible for the respective objectives fulfilment (Swedish Environmental Protection Agency [SEPA], 2009b).

As one of many actions considered necessary, a national inventory of contaminated soils assessed and classified in accordance with standardised environmental risk criteria was prompted early on. Although the full inventory is yet to be completed, in 2009, the identification-stage was deemed nearly complete, indicating just over 80 000 sites of potential soil contamination nationwide. Unfortunately but perhaps not too surprisingly, many of the identified sites have shown to a) suffer from poor stability and b) be located adjacent to surface waters. This as a result of the tendency of the industrial activities typically responsible for the contamination, and oftentimes also for the destabilisation of the soils, being placed along the shores of open waters for processing and transportation purposes (SEPA 2009a; Larson et al., 2007). For a country that extracts roughly 50% of its water supplies from various surface water systems (Svenskt Vatten, 2009), and for a country with major environmental conservation values in connection to many of its lake, river and ocean coasts, this poses a serious threat to its environmental and societal welfare. Concerns are further exacerbated by worries over predicted effects of future climate change, which is nationally expected to increase rates of erosion and probabilities of mass failure through increases in precipitation and run-off (Fallsvik et al., 2007).

As a response to these concerns, in 2007, the Swedish Geotechnical Institute (SGI), being appointed the governmental expert body for national mass movement hazards, in collaboration with Lund University, initiated a research project aimed at assessing and reducing risks relating to the spread of pollutants in surface water systems due to slope failure. The overall objective is stated as "*to develop a model of the processes that control the release and transport of contaminants in surface water following slope failure with contaminated soil and to formulate guidelines for assessment of contaminated areas that are at risk of experiencing slope failure*" (Larson et al., 2007). As such, although the focus first and foremost lies on Swedish conditions and concerns, the approach and interest is and ought to be universal.

Initial research outcomes are presented in Göransson et al. (2009). Relevant existing Swedish risk assessment methodologies are reviewed, the presence of contaminated soils at risk of slope failure along the Göta Älv river valley investigated, and a first conceptual model of the hazard is hypothesised based on generally acknowledged theoretical understandings. Through compiling and analysing documentation of nationally experienced mass movements, this study seeks to evaluate the validity of the proposed model *and* to assess the broader national extent of the hazard. Specific aims are as follows:

- to characterise the distribution, occurrence and mechanics of mass movements occurring into Swedish surface water systems,
- to review observed short- and long-term effects on affected surface water systems and analyse some of the processes and factors decisive in determining the fate of sediments and pollutants potentially released, and,
- to generally investigate the potential national scope of the hazard through a selected number of case studies.

1.2. Adopted hazard and risk terminology

The hazard and risk terminology applied in this study is derived mainly from the '*Disaster Risk Reduction Glossary'* developed by the United Nations International Strategy for Disaster Reduction (UNISDR, 2009). Adopted definitions of key terms are:

- **hazard**: a potentially damaging physical event, phenomenon (or human activity) that may cause the loss of life or injury, property damage, social and economic disruption or environmental degradation
- **hazard analysis**: identification, studies and monitoring of any hazard to determine its potential, origin, characteristics and behaviour
- **risk**: the probability of harmful consequences, or expected losses (deaths, injuries, property, livelihoods, economic activity disrupted or environment damaged) resulting from interactions between natural or human-induced hazards and vulnerable conditions. Risk (R) may be expressed as hazard/-s (H) * vulnerability (V)
- **risk assessment/analysis**: a methodology to determine the nature and extent of risk by analysing potential hazards and evaluating existing conditions of vulnerability that could pose a potential threat or harm to people, property, livelihoods and the environment upon which they depend
- **risk management**: the overall application of policies, processes and practices dealing with risks
- **vulnerability**: the conditions determined by physical, social, economic and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards

2. Materials and methods

This study has been formulated and conducted mainly as an extensive literature study and analysis of documented Swedish mass movement events. Since no complete, systematic compilation of such events currently exists, relevant information has been sought for through a variety of media.

2.1. Data compilation

The primary source of information has been an as of yet unofficial *proposition* of a national mass movement database managed by SGI. The database is a Microsoft Access-database and at present lists 157 dated and 259 undated events; the latter of which are based purely on geomorphological observations. For each recording, the database lists type of movement, geographical position, geological conditions and relevant references. For some events, date, geometry of movement and slope, observed geotechnical conditions, use of land and recorded damage has also been listed. It should be noted that gullying and minor erosional events are also registered in the database. However, these events have not been accounted for in this study. Only types of movements classified in accordance with the terminology introduced by Varnes (1978; see chapter 3.2) have been included here. That totals 393 falls, slides, spreads and/or flows.

In order to sort out those registered events occurring into surface water systems – hence those events relevant for this study – Sweden's County Administrative Boards and Water Authorities interactive *Water Map* (2009) has been used to cross-check given coordinates. For identified relevant events, (in the database) noted references have then been studied for further information. These references have covered everything from daily newspapers, student theses, scientific journal articles, SGI-reports, local/regional/governmental building plans and prospects to geological map descriptions.

Additionally, supplementary information on relevant events as well as information on potential *unregistered events* has been sought for through systematic questioning of appropriate governmental authorities (e.g. Geological Survey of Sweden [SGU], Swedish Meteorological and Hydrological Institute [SMHI], Swedish Environmental Protection Agency, Swedish Civil Contingencies Agency [MSB], Swedish Maritime Administration, Swedish Board of Fisheries), County Administrative Boards, municipalities, water authorities/management organisations and various research institutes. Newspaper articles relating to geotechnical matters/incidents have also been examined at the library at SGI in Linköping, and simple web-searches using Google have also been conducted.

2.2. Field visits

Two of the most mass movement-affected areas in the country were visited for general reconnaissance-purposes. In addition to their high mass movement-frequency, the two were chosen because of dissimilarities in terms of geography, geology and hence type of mass movement activity. One of the areas was the Ådalen region in Västernorrland along the river Ångermanälven; a sparsely populated, forest-dense and relatively "wild" area. Åke Gullersbo of Sollefteå Municipality acted as a guide and several sites of recent mass movement activity, as well as sites at risk of failure, were visited. Mitigation measures, general attitudes and historical experiences were discussed.

The second area visited was the southernmost part of the Göta Älv river valley in south-western Sweden. This is (in contrast to Ådalen) one of the most densely populated and most exploited areas of all in Sweden. It is also here that the most devastating mass movements in the country have taken place. In addition to a SGI-guided boat trip along the river during which historical as well as future potential sites of mass movement activity were studied and discussed, a visit was made at one of the municipal water treatment plants at which effects of some more recent mass movements have been noted (Göta Älv serves as a regional freshwater resource).

2.3. Hazard analyses

For the three hazard analyses presented in chapter 7.1, geographical information on

- *mass movement susceptibility* based on standardized stability mapping measures as further described in section 5.3.1,
- *sites of potential soil contamination* based on standardized national inventories of such as further described in section 6.3.1, and,
- *environmentally hazardous facilities* based on national and regional registers of the same as further described in section 6.3.2,

was collected and combined in ESRI ArcGIS in order to visualize and evaluate potential risk areas. Base maps were provided for through Lantmäteriet; the Swedish Mapping, Cadastral and Land Registration Authority.

For Klarälven, geographical information as well as additional information on specific risk objects (sites of potential soil contamination and/or environmentally hazardous facilities) was provided for by the County Administrative Board of Värmland (if not stated differently).

For Ångermanälven, digital georeferenced stability maps were provided for by SGI with the permission of MSB. Geographical as well as additional information on sites of potential soil contamination as well as sites of environmentally hazardous facilities were provided for by the County Administrative Board of Västernorrland (if not stated differently).

For Viskan, stability maps in Adobe Illustrator-format were provided for by Mark Municipality together with selected parts of their geodatabase. Using ArcGIS, these maps were georeferenced and converted into shp-format. Geographical as well as additional information on sites of potential soil contamination as well as sites of environmentally hazardous facilities was provided for by the County Administrative Board of Västra Götaland (if not stated differently).

3. Mass movements - a theoretical framework

3.1. Defintion

Mass movements (also mass transports, slope movements, mass wastings, mass failures, slope failures, landslides) are defined as "*the downslope movement*(s) *of soil or rock material under the influence of gravity without the direct aid of other media such as water, air, or ice*" (Selby, 1993:249). Depending on the physical properties of the mobilised material, the surrounding environment and the mode and mechanism of deformation, the scale and nature of the movement will vary. Hence, the range of potential processes and effects is immense.

3.2. Classification and terminology

3.2.1. Forming names: Categorization, key criteria and order

The most widely adopted classification scheme for mass movements is that of Varnes (1978) within which three types of material - *rock*, *debris* and *earth* - and five main types of movement - *falls, topples, slides*, *spreads* and *flows* - are recognized and combined so as to cover the full span of potential processes (n.b. this excludes ground subsidence and collapse as well as snow avalanches and ice falls) (fig. 3a). *Rock* is defined as a hard or firm mass that was intact and in its natural place before the initiation of mass movement, *debris* as a material in which less than 80% of the particles are smaller than 2 mm (>20% is medium sand or coarser sediment grades) and *earth* as a material in which more than 80% are smaller than 2 mm (>80% is fine sand, silt or clay grades).

Any type of mass movement can and should be named, classified and described according to a minimum of these two criteria (material and movement) (Cruden & Varnes, 1996). Based on the amount of information available, other defining attributes and other defined descriptors can and should be taken into consideration and added to the basic two-noun name in a determined order so as to provide an as elaborate and as consistent representation of the movement as possible. Preferred criteria and taxonomic order is:

- (state, distribution and style of) activity
- rate
- water content
- material
- movement

Descriptors for each one of these criteria respectively are presented in table 3i. For further definitions, see Cruden & Varnes (1996).

3.2.2. Morphometry

The most comprehensive nomenclature of mass movement features is that originally put forward by Varnes (1978) (fig. 3b), later also adopted by the International Association for Engineering Geology and the Environment's Commission on Landslides [IAEG] (1990). By revising the original figure, IAEG produced a general, conceptualized mass movement diagram in which numbers instead of names are applied to identify known features, thereby enabling universal use when accompanied by a language-specific definition table (fig. 3c). The diagram was further reproduced and relabelled so as to demonstrate typical mass movement dimensions.

It should be noted that the diagrams, features and dimensions demonstrated are based mainly on *rotational earth slide-earth flow* movements.

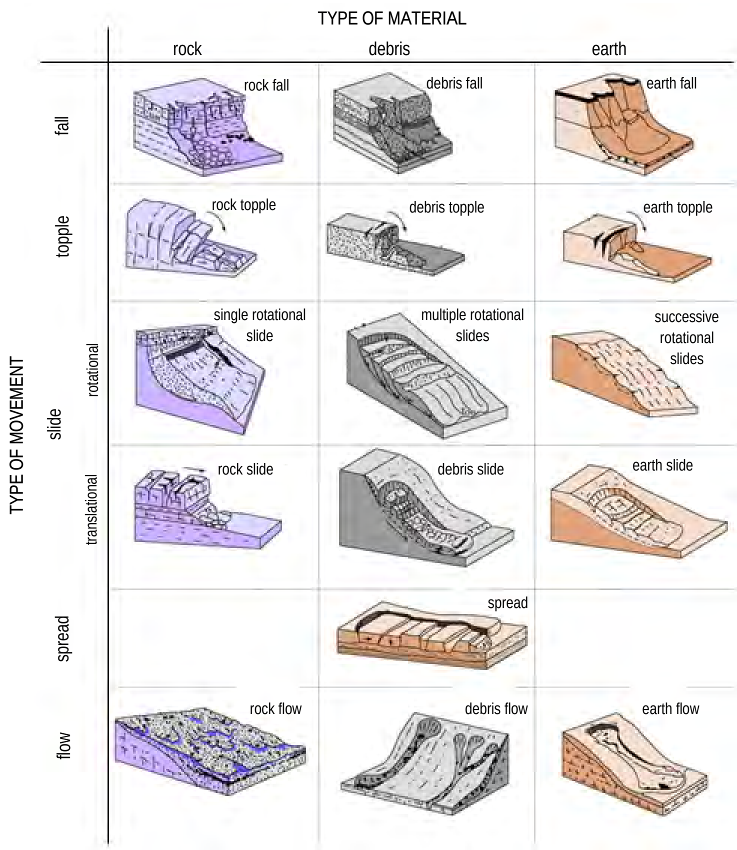


Figure 3a. Fundamental mass movement classification. After Varnes (1978), figure modified from GeoNet (2009).

ACTIVITY			RATE	WATER CONTENT	MATERIAL	MOVEMENT
STATE	DISTRIBUTION	STYLE				
Active Reactivated Suspended Inactive Dormant Abandoned Stabilized Relict	Advancing Retrogressing Widening Enlarging Confined Diminishing Moving	Complex Composite Multiple Successive Single	Extremely rapid Very rapid Rapid Moderate Slow Very slow	Dry Moist Wet Very wet	Rock Debris Earth	Fall Topple Slide Spread Flow

Table 3i. Mass movement classification: key criteria and associated descriptors for forming names. After Cruden & Varnes (1996).

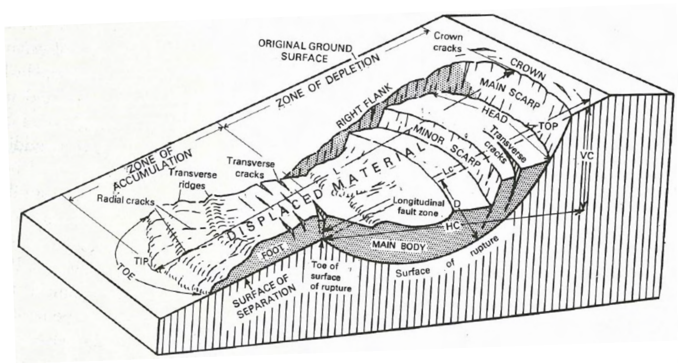


Figure 3b. Idealised diagram of an earth slide-earth flow illustrating typical mass movement features. From Cruden & Varnes (1996).

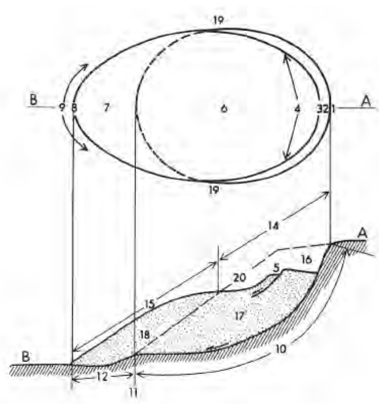


Figure 3c. Mass movement features and nomenclature. After IAEG (1990).

NO.	NAME
1	Crown
2	Main scarp
3	Top
4	Head
5	Minor scarp
6	Main body
7	Foot
8	Tip
9	Toe
10	Surface of rupture
11	Toe of surface of rupture
12	Surface of separation
13	Displaced material
14	Zone of depletion
15	Zone of accumulation
16	Depletion
17	Depleted mass
18	Accumulation
19	Flank
20	Original ground surface

3.3. Types and processes

Key physical characteristics of the five main types of mass movements listed earlier (also see fig. 3a) are described in this section. It should be noted that although the different types of movements *may* be easy to distinguish from one and another, such is not always the case. Complex, compound types are common and one type may effectively grade into another with time, extent and potential alterations in deformation mechanisms.

Falls

A fall is defined as the transport process by which a mass initially and predominantly moves freely through the air. It is a relatively simple type of mass movement that typically occurs off steep slopes/faces of cohesive soils or weak rock rich in closely spaced and steeply inclined joints, bedding planes and/or exfoliation surfaces. The movement is typically very rapid to extremely rapid, may involve rolling and/or bouncing and is oftentimes preceded by more or less pronounced sliding or toppling movements effectively separating the displacing material from the undisturbed mass (Cruden & Varnes, 1996). Displaced material may accumulate as a scree (talus) cone along the base of the cliff face/slope.

Topples

A topple is defined as the forward rotation and resultant transport of a mass about a pivot. It can be considered a special type of falling, likewise occurring off steep slopes/faces of cohesive soils or weak rock rich in closely spaced and steeply inclined discontinuity surfaces (Bell, 1999:124). Rate of movement ranges from extremely slow to extremely rapid (typically accelerating) and depending on type and geometry of material, as well as mode and surface of deformation, a topple may eventually evolve into a fall or a slide (Cruden & Varnes, 1996).

Slides

A slide is defined as the down slope movement of a mass along a well-defined slip surface (Bell, 1999:127). Rate of movement ranges from extremely slow to extremely rapid and the area of deformation, together with the surface of rupture, typically expands throughout the movement.

A distinction can and should be made between the two main types of sliding; *rotational* and *translational*. These two types are normally easy to distinguish from one and another, but compound, complex types do occur (Cruden & Varnes, 1996).

Rotational slides (also slumps) occur along curved, concave approximately spoon-shaped slip surfaces and are especially common in soft rocks (e.g. shales and mudstones) and overconsolidated clays (Selby, 1993:259-260). Backward rotation is the main mechanism of movement, tilting the surface of the displaced material backwards towards the main scarp meanwhile leaving the latter close-to-vertical and unsupported. This normally results in a series of retrogressive, rotational slides (along the same basal slip surface) developing in a headward direction (Bell, 1999:127). The grade of internal deformation is typically low. Undrained and gradually ponded depressions tend to form along the progressively lowered main scarp, potentially further adding to the maintenance of the deformation and the movement and in cases also triggering flows (Cruden & Varnes, 1996; Selby, 1993:260).

Translational slides (also block slides, planar slides) occur along planar or slightly undulating and typically shallow surfaces (Cruden & Varnes, 1996). Hence, they are common in horizontally jointed and/or stratified deposits and along boundaries between materials of different physical properties. Depending on the steepness of the surface of rupture, translational sliding may once initiated progress as good as unrestrained and at accelerating velocities; especially if/ when air gets trapped beneath the displacing mass, thereby virtually reducing the friction between the surface of rupture and the moving mass to zero. If deformation and water content increases down slope, a translational slide may eventually evolve into more of a flow (Bell, 1999:129).

Spreads

A spread is defined as the fracturing and/or lateral extension of a cohesive soil or rock mass over a deforming mass of softer (typically sensitive), underlying material (Selby, 1993:260). It is a physically complex type of mass movement, typically very rapid and may involve everything from subsiding to translation, (mainly retrogressive) rotation, disintegration, liquefaction and flowing (Cruden & Varnes, 1996). Geomorphic alterations are typically major (Selby, 1993:260).

Flows

Flows are mass movements in which the behaviour of the displacing mass resembles that of a viscous fluid (Cruden & Varnes, 1996). Water content is thus normally imperative causing extremely mobile and very rapid movements. However, short-lived dry flows of millions of tonnes of material (e.g. rock avalanches) do occur (Picarelli et al., 2005; Bell, 1999:129). Progressive failure is common and oftentimes lead to loss of cohesion within the displacing mass and extreme velocities of up to 30 m/s (Bell, 1999:129). Lahars are flows of volcanic material.

3.4. Governing factors: causes and triggers

Mass movements occur when forces encouraging movement of a mass off a slope (disturbing forces, M_D), exceed forces withstanding it (resisting forces, M_R) (fig. 3d). Their occurrence is dependent on the relation between gravitational and residual (shearing) stresses imposed on a mass on the one hand, and the shear strength of that mass as well as eventual counterweights on the other. Slope load, height, inclination,

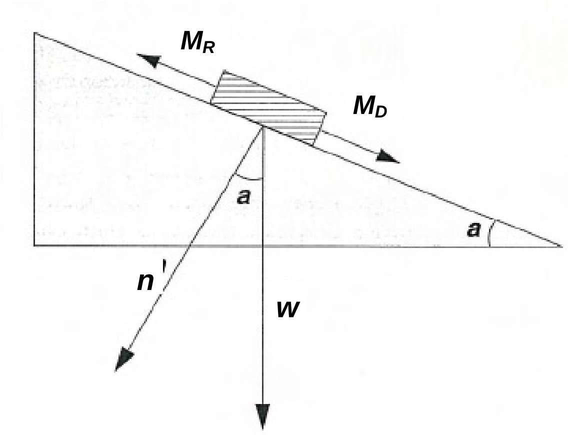


Figure 3d. Simplified relationsip between the driving forces (M_D) and the resisting forces (M_R) on a mass on a natural slope. After Smith (2001:186). w = weight of mass, a = inclination of slope, n = normal force.

support and pressure are key parameters decisive of the former. The latter is dependent mainly on weight, cohesion and friction of the specific slope material. Groundwater conditions, especially pore water pressure conditions, are also of major importance. Table 3ii summarises the most fundamental mechanisms potentially leading to mass movement occurrence. A distinction is made between:

- *external* mechanisms, causing failure of a mass through increasing imposed disturbing forces (M_D) to a level beyond the inherited shear strength (M_R) of that mass, and,
- *internal* mechanisms, causing failure of a mass through decreasing its shear strength and thus its resisting forces (M_R) to a level below that of imposed external, disturbing forces (M_D).

The ratio between the two sets of forces can be denoted by a *factor of safety* (F), describing the *slope stability;*

$$F = M_R/M_D$$

The greater the value of F, the greater *the probability of stability* of the slope (there is no such thing as absolute stability) (Selby 1993:268). F = 1 denotes a situation wherein the slope is at *the boundary of failure*. Calculated values of $F \leq 1$ is indicative of an unstable slope in condition for failure.

In addition to the separation made between the external and the internal mechanisms, there is an important distinction to make between those brought about by *natural processes* and those resulting from *human activities*. Five overarching governing factors in terms of mass movement occurrence can be recognised:

- **geological conditions**; responsible for inherited soil and slope properties (including hydrogeological properties), and fundamentally decisive of rate and means of influential natural processes (e.g. erosion, weathering, tilting)
- **climatic conditions**; influential of rates of weathering and hydrogeological and hydrological settings and processes (e.g. pore-water pressure-alterations and run-off and erosion intensities)
- **biological conditions**; decisive of grade of vegetative support/loading of slope and influential of rates of erosion and weathering
- **anthropological influences;** potentially interfering with-, and hence modifying any of the above.

It is important to recognise the relationship and interdependency between all of the above listed factors/ conditions. As stated by Selby (1993:275); a particular movement *"can seldom be attributed to a single definite cause although it may be possible to identify a dominant or a triggering effect"*.

3.5. Assessment

3.5.1. Hazard analysis

Mass movement hazard analysis refers to the identification and characterisation of materials at risk from mass failure. Governing factors - geological, climatic, biological and anthropological conditions - within a given risk-area is investigated in order to assess existing and potential future measures of slope stability. Adding to this is the study of historical and geological records of movements so that probabilities of occur-

External mechanisms - causing an increase in the disturbing forces M_D on the slope material	
Type	Possible agent (-s)
increase in slope angle	tectonic tilting // stream/glacial erosion // dredging // construction works
removal of lateral/underlying support	stream/glacial erosion // reduction in water table // weathering (wetting/drying/frost action) // dredging // quarrying
overloading on slope	snow // rain // talus // fills // waste // structures
increase in lateral pressure	freezing // clay swelling
imposition of transitory stresses (increase in external stresses, reduction in pore space)	seismic activity // explosions // traffic // construction works
removal of vegetation (loss of soil binding, alterations of hydrological/hydrogeological conditions)	wildfires // logging // overgrazing // construction works
Internal mechanisms - causing a reduction in the resisting forces M_R on the slope material	
Type	Examples of agent (-s)
alterations to composition/texture/structure of slope material	weathering (physio-chemical reactions/wetting/drying/frost action/burrowing/piping)
increase in pore water pressure	rainfall // snowmelt // flooding // artificial infiltration

Table 3ii. Mechanisms potentially leading to mass failure (Smith, 2001:188-191; Bell, 1999:118; Selby, 1993:276, Varnes 1978:26-28).

rences can be assessed. When combined in statistical, geological and geotechnical models, *estimations of* probable types, behaviours, velocities, travel-paths, run-out distances and frequencies of movements can be made (Picarelli et al., 2005).

Real-time monitoring of slopes/materials at risk from failure represents a further means of mass movement hazard analysis. Many types of mass movements are preceded by minor movements (Bell, 1999:144). If detected, such movements may assist in characterising and potentially also mitigating future deformation and failure. Measurements of surface as well as subsurface vertical and horizontal movements might thus prove valuable. This can be done using a variety of techniques, including conventional surveying, remote sensing, laser/electronic distance/crack measurements and by use of instruments such as tiltmeters, extensometers, inclinometers and deflectometers. Seismographs and geophones might further assist, potentially detecting acoustic emissions in connection to any movements (Bell, 1999:150). Such measurements may also help determine location and extent of deformation surfaces. Furthermore, monitoring influencing disturbing forces such as water levels, pore water pressures and loads is of course likewise, if not more, important in that it might help in mitigating movements before they have been initiated at all.

3.5.2. Risk analysis

The ultimate effects of mass movements are not solely a function of their physical behaviour. A mass movement risk analysis considers and evaluates the *full* potential consequences of an identified mass movement hazard. Thus, it adds the element of vulnerability to the concept of danger. In addition to the actual hazard analysis, population densities, coping potentials, societal and environmental values are then also analysed so as to give an as complete and accurate assessment of actual risks as possible. Geographical Information Systems are a powerful tool in this context, enabling joint assessment of the character of the physical hazard on the one hand, and potential elements at risk on the other.

4. Mass movements as contamination carriers - the concept

4.1. Process scenario

Fig. 4a illustrates the processes and properties governing the release and transport of contaminants due to slope failure into surface waters according to the original hazard conceptualisation hypothesised by Göransson et al. (2009). It is the so far only known system description of the hazard.

A distinction is made between the:

- **initiate zone**; from which the movement originates,
- **run-out zone**; within deposition occurs for most of the moving masses, and,
- **2nd run-out zone**; defined as *"…a further run-out zone into the surface water when the transported soil is suspended into the water"* (Göransson et al., 2009:38).

The process is described based on a division made between the instantaneous and the long-term release of materials. The *instantaneous* or *near-field* release represents that of the triggering of the event, and that

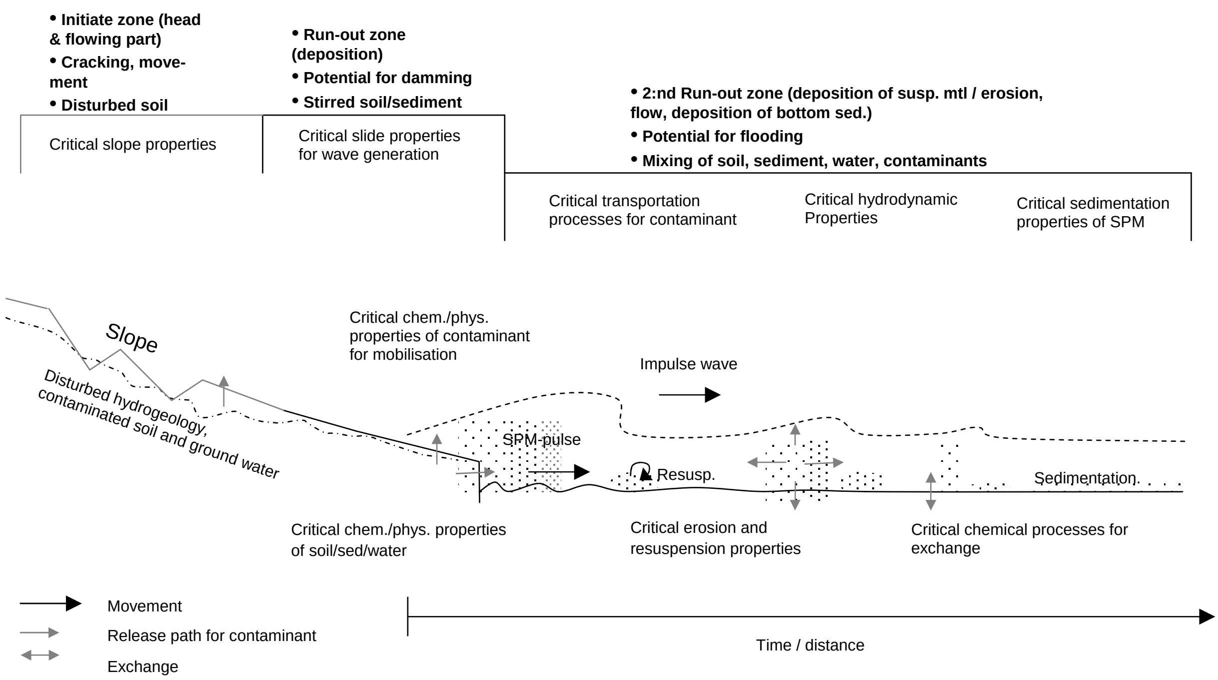


Figure 4a. Processes and properties governing the release and transport of contaminants due to slope failure into surface waters (Göransson et al., 2009).

of the perpendicular movement of the mobilised material into the SWS. Contaminant mobilisation is considered plausible through:

i. the disturbance, mixing and exposure of soils, sediments and groundwater to the air and SWS within the initiate zone,
ii. the stirring and exposure of soils and sediments to the SWS within the run-out zone, and,
iii. the further far-field transport of materials set into suspension through stirring of soils and sediments into the 2nd run-out zone. Based on observations made on the character of storm-induced flood waves, this transport is hypothesised to occur in pulses with the main pulse occurring on the rising limb of the impulse-generated, radially propagating wave (surge) likely to form in conjunction to the main movement.

Contaminant mobilisation from within reaches struck by the surge and/or the initial rise in water level caused by the transport of material into the water reaches is also considered part of the instantaneous release.

The *long-term* release of materials is defined as that occurring after the *"...hydraulic regime returns to normal conditions..."* (Göransson et al., 2009:39). It represents the continued mobilisation of contaminants from displaced materials through resuspension, diffusion, desorption and dissolution.

Spread of contaminants in connection to mass movements may hence be volatile (within the initiate zone), solute and/or particle-bound (within the run-out zones).

4.2. Decisive factors

The fate and effects of materials (sediments, contaminants) displaced into a SWS through slope failure will essentially be controlled by:

- the displaced geological material(-s) hydraulic mobilisation potential,
- the displaced contaminant(-s) chemical mobilisation potential, and,
- the bioavailability of the displaced contaminant(-s).

According to Göransson et al. (2009), specific governing factors can be divided into critical *slope and slide properties, chemical/biological/physical properties of the soils/sediments/contaminants/water*, and, *hydrodynamic properties of the SWS.*

Slope and slide properties can be assumed to define the type and magnitude of the movement, hence the inherited state and energy (mobilisation potential, bioavailability) of materials involved, and thus the imposed potential of the hazard. Governing factors in terms of mass movement occurrence within the initial zone as described in section 3.4 are critical in this context, so is geology/geomorphology of immediately surrounding reaches. Göransson et al. (2009) mentions slope aspect, undisturbed shear strength, pore water pressure within the initial zone and geometry and composition of media within the run-out zone as especially imperative.

Upon entry into the run-out zone(-s), the inherited mobilisation potential of involved materials will be influenced by *the chemical, biological and physical properties of surrounding reaches and media*. This includes the chemical, biological and physical properties of the air, the water body and disturbed soils and sediments incorporated into/affected by the movement. Grain size, density, organic carbon content/supply and grade of bioturbation are likely key concerns for the soils/sediments potentially involved (Göransson et al., 2009; Larsen et al., 2007). So is redox potential, pH and temperature which is also critical for the state and properties of the water body. For contaminants involved/potentially involved; solubility, vapour pressure, biodegradability, adsorption properties and stability (phase) are to be considered key governing factors (Göransson et al. 2009; Andersson-Sköld et al., 2007; Westrich & Förstner, 2007).

It is *the hydrodynamic properties of the SWS* that will govern the long-term release and transport of contaminants in accordance with the above. Discharge rates and carrying capacities, circulation patterns, composition and micro/macro-scale morphology of surrounding reaches are the key factors that will determine a) to what extent displaced materials will be transported within the SWS, b), to what extent up/ downstream reaches will be integrated into the movement, and, c), where transported materials will be deposited. An important aspect of the hydrodynamic properties to bear in mind is the imposed alterations to those potentially brought about by the movement itself. Hydrodynamic properties, and to a certain extent also the chemical and biological properties of involved media, is also influenced by climatic conditions and may accordingly vary seasonally.

4.3. Environmental concerns

The most obvious environmental concern of the mass movement-contaminant release and transport hazard is that of the spread of toxic substances throughout involved media. Associated effects/risks will be determined by the scope of the hazard according to the above, and, by the vulnerability (resilience) and imposed environmental and societal values of affected reaches.

Another aspect of the hazard is that of the imposed rearrangement of the physical surroundings and associated alterations to the entire hydrodynamic system. Depending on the extent and character of these alterations, environmental damage can be hypothesized through e.g. modifications of nutrient circulation patterns, damage to natural habitats and through a reduction in visibility, light transmission, oxygenation thus potability and bioproductivity of involved ecosystems in connection to the stirring and suspendation of soils/ sediments (Schuster & Highland, 2007; Meehan, 1991:152-166). Such concerns are plausible with or without the involvement of contaminated material.

5. Mass movements in Sweden

In the following chapter, the extent and character of Swedish mass movement hazards is briefly described based on what can be deduced from existing literature *and* recordings made in the national mass movement database presented in chapter 2. Trends, authorities and mitigation measures are also reviewed.

5.1. The geological context

The Swedish landscape is one of great variety. It has evolved over nearly three billion years through a wide array of geological processes. Morphology, structure and composition of both bedrock and soil have been altered through repeated orogenies and glaciations, through periods of intense volcanic and earthquake activity, through heavy erosion (peneplanation) and through isostatic fluctuations at different spatial and temporal scales. Climate has varied and flora and fauna alike. The shapes that form and the materials that cover the surface of the Swedish landmass today, however, is to a large extent a result of Quaternary glaciation and deglaciation events (Wastenson & Fredén, 2002). It was only ~10 000 years ago that the last parts of the latest Fennoscandian continental ice sheet left the northernmost parts of Sweden (whose borders it once covered completely), leaving behind a partly inundated, substantially altered, young and relatively unstable landmass covered in thick glacial and postglacial deposits still undergoing substantial isostatic rebound.

Since then, land uplift has continued whereby previously submerged lowlands have gradually come to rise above the sea surface. Considerable volumes of fine-grained marine, lacustrine and fluvial deposits have accordingly been subaerially exposed. Meanwhile, erosion, inclination and overall sensitivity of slopes within and around those deposits have increased. The gradual decrease in the base level of adjacent rivers and lakes that followed upon the lowering of the sea level is one reason for this. Gradual leaching of salts from and within marine deposits is another. Consequently, substantial parts of the Swedish landmass have come to suffer from geological conditions prone to mass failure.

5.2. Distribution, types and frequencies

Fig. 5a illustrates the nationwide mass movement hazard with respect to the known occurrence of mass movement scars (SGU, 2009) and events as documented in the national mass movement database (SGI, 2009). The geological conditions discussed are evident in that as good as all areas of high to intermediate frequencies (thus risks) lie well below the highest coastline, north of the boundary for pronounced upheaval of land and/or in areas bordering open waters.

The most affected region is that of Västra Götaland County along the north of the west coast, in and around the city of Göteborg (Sweden's second largest; ~910 000 inhabitants). About 50% of all events documented in the database have been recorded in this region (however, the number might be somewhat misleading as documentations here are likely to be overrepresented due to relatively high population densities over long periods of time, and, due to a long history of regional mass movement hazard studies). The majority of the documented events here have occurred in the thick (up to one hundred metres), relatively loose, homogenous and partly highly sensitive marine glacial and postglacial clays and quick clays of the Göta Älv river basin downstream Lake Vänern. According to SGU (2009), approximately 500 million cubic metres of material have been eroded within this major (Sweden's largest) river basin in connection to historical mass movement activity; much through frequent small and shallow earth sliding events, but much as well through rarer but more major progressive and retrogressive rotational earth sliding events. Viberg et al. (2001) estimated that slides involving more than 10 000 m^2 of land occur approximately once every third year within this area. Furthermore, several events through which land areas of several hundred thousand square metres have been displaced have also been recorded throughout historical times. Examples are Jordfallet (1150; ~0.51 km^2), Intagan (1648; ~0.27 km^2), Surteskredet (1950; ~0.27 km^2), Götaskredet (1957; ~0.37 km^2) and Tuveskredet (1977; ~0.27 km^2). There is a clear tendency for the movements in this area to occur during autumn when rainfall is at an annual high and run-off intensities and pore-water pressures are seasonally increased (Viberg et al., 2001; Wenner, 1951).

Earth slides are also relatively common along the shorelines of rivers further inland (e.g. Klarälven, Norsälven and Vrångsälven). However, here they are generally smaller and less frequent than in the west. This is mainly considered to be due a marked difference in the physical properties of the sedimentary deposits of which a much greater proportion in these areas are of glacial origin. Hence, they are generally much thinner, much firmer and thus less sensitive to deformation and transport when compared to those of the Göta Älv river basin (Hultén et al., 2005). Still, major events involving the displacement and further transport of several tens of thousands of square metres of land have occurred here as well (e.g. Trossnäs 1969; ~0.52km^2). These events have not only been restricted to earth slides; earth falls and flows have also been documented.

Although mass movements also do occur in certain areas along the south of the east coast of Sweden (e.g. Within Östergötland and Stockholm counties), they are rather rare and especially so when compared to those of the south of the west coast. There are no major rivers in this area as is the case further west and north. Consequently, the movements that do occur in this area mainly do so either in connection to the sea, or in connection to lakes. Earth and debris slides are the most common type of movements although some rock falls have been documented.

The regions surrounding the great rivers of the

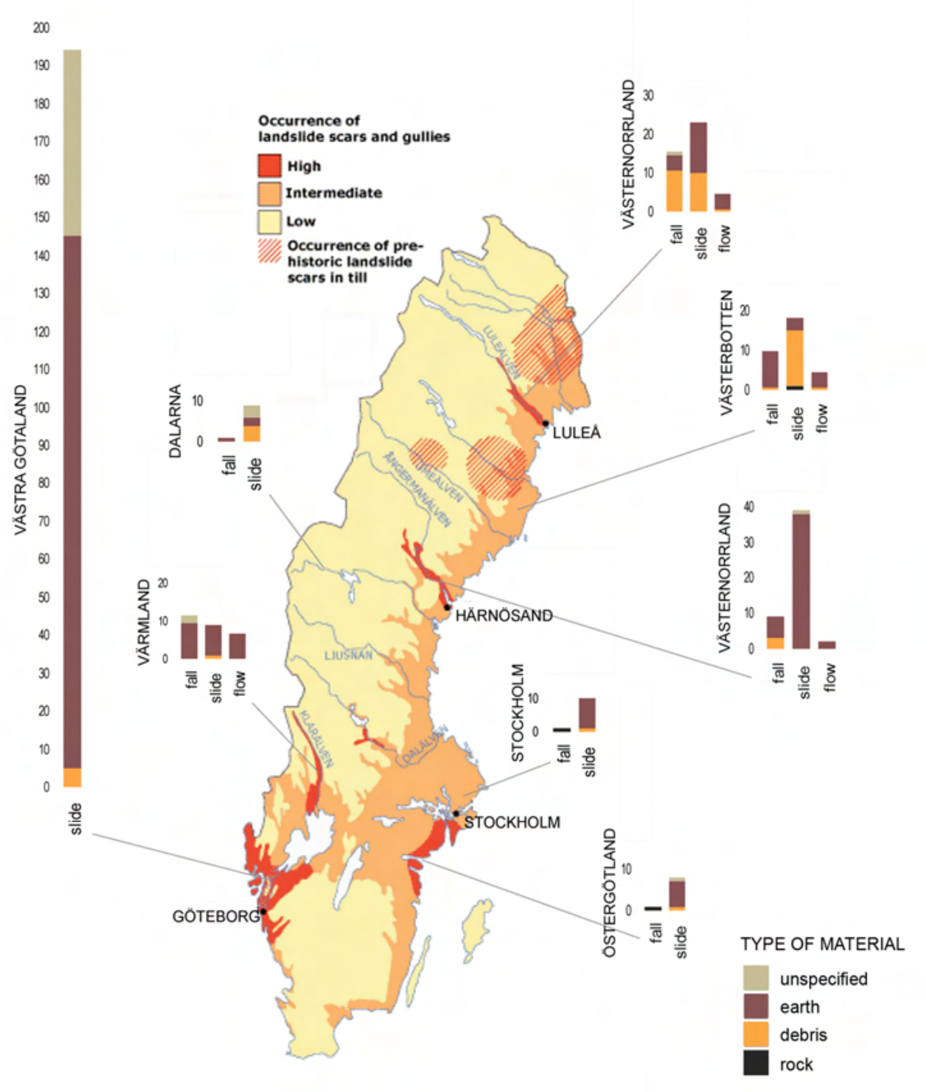


Figure 5a. Overview of the Swedish mass movement hazard as indicated by:
(i) the known occurrence of mass movement scars (base map; SGU, 2009) and,
(ii) events per county as documented in the national mass movement database (column bars). Only counties for which there are >5 events documented have been accounted for here.

north (mainly Ångermanälven, Umeälven, Piteälven and Luleälven) represent further areas of frequent mass movement occurrences. These are the areas in Sweden for which isostatic uplift is and has been absolutely most pronounced throughout the past thousands of years. The current rate is ~9mm/yr which is the highest rate nationally (SGU, 2009). The rivers mentioned have all developed first as pathways for glacial melt water whereby a range of materials predominated by fine-grained sand, silt and some clay have been deposited along and around their courses (Hultén et al., 2005). As land uplift has progressed, the rivers have cut down rapidly through their own deposits whereby bluffs of up to 50 metres in height and up to 45º in mean inclination have come to form (Svensson et al., 2006). Such bluffs are theoretically too steep to be standing. Negative pore water pressures and cementation effects within the soil act stabilising, however, movement is unavoidable and frequent, particularly during spring in connection to snow-melt when stream erosion and weathering through freeze/thaw action is especially prominent. The main types of movements in these regions are small to moderately sized earth and debris falls and/or translational slides. Major events are relatively uncommon and mainly restricted to more clayey regions wherein movements that resemble rotational slides, i.e. with a certain degree of curvature to the slip surface, have been known to develop (Svensson et al., 2006). Sporadic flows have also been recorded here.

Although not highlighted in fig. 5a, it should be noted that rock and debris falls and flows are rather common in the more mountainous areas of north-western Sweden. These are regions that in places can be very rich in relatively sensitive tills and/or weak, jointed bedrock (Fallsvik et al., 2007). However, due to the fact that this is an area extremely sparsely populated, few recordings of movements have been made. Occasional debris flows are also known from regions characterised by steep fault lines, e.g. in the areas around the southern parts of Lake Vättern.

Concluding, mass movements of different spatial scales occur repeatedly in Sweden and are mainly concentrated to river basins located (i) well below the highest shoreline and, (ii), in connection to areas along the north of the west- and the north of the east coast. Earth slides are the overall most frequent type of movement with rotational events in clays being those most common in the south, and translational events in (mainly) silts being typical for the more northern areas where also earth and debris falls and flows occur occasionally. Movements are especially common during autumn in south-western Sweden, and during spring in northern Sweden.

An important point to make is the potential modification of national mass movement frequency and distribution in relation to predicted future alterations of regional, and local, climatic conditions. Modelling conducted by the Swedish Meteorological and Hydrological Institute (SMHI, 2005) has indicated that the national annual average temperature may increase with ~2.5-4ºC until the year 2100 due to human greenhouse -gas emissions. If so, rates of precipitation and run-off may increase with as much as 30% meanwhile (SMHI, 2005), thereby increasing rates of erosion, pore-water pressures and potentially also mass movement frequencies in many parts of the country (Fallsvik et al., 2007) (fig. 5b).

Furthermore, there is the hypothesised global sea-level rise to bear in mind. Inland, this rise may in places act stabilising through increasing base-levels of rivers, hence increasing slope support. In coastal areas, however, it may add to mass movement concerns as wave and wind erosion is likely to become more prominent (Hultén et al., 2005). Finally, more pronounced and hastier temperature-changes have also been hypothesised (Fallsvik et al., 2007). These would also be likely to increase mass movement frequencies through increasing rates of weathering through freeze/thaw-processes. Forecasts are clearly complex but potential scenarios nevertheless important to bear in mind.

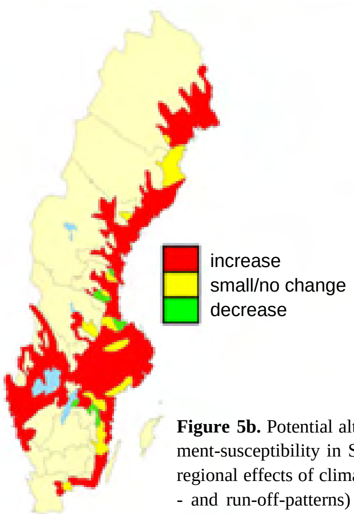


Figure 5b. Potential alterations to mass movement-susceptibility in Sweden due to predicted regional effects of climate change (precipitation - and run-off-patterns) up to the period 2071-2100. From Fallsvik et al. (2007).

5.3. Responsibilities and mitigation measures

The ultimate responsibility for safety and health issues regarding mass movement hazards and risks within a defined area in Sweden lies with the specific landowner. However, there are governmental authority missions, bodies, hierarchies and contribution systems implemented so as to identify, enforce, guide and support relevant and in some cases defined and legislated mitigation measures. The two main bodies of authority in this context are the Swedish Civil Contingencies Agency who is assigned with the overall governmental authority mission of responsibility for matters related to civil protection, emergency management and civil defence, and, SGI. The latter acts as a governmental expert body for matters relating to mass movement hazard management, thus having more of an advisory role. These are the bodies within which monetary funds, relevant tools and theoretical expertise are primarily to be found and channelled, and, through which relevant research, education and legislation is fundamentally implemented.

5.3.1. Hazard and risk management

Except for research, education and direct relief aid in connection to actual mass movement events, the main means of Swedish mass movement hazard and risk management is through standardised slope stability mapping in accordance with an investigation program delineated and launched by the Royal Swedish Academy of Sciences' Commission on Slope Stability in the late 1980s (see Axelsson et al., 1995). The program recognises four stages of investigation of which the first is an *"overview mapping stage"* whose yet-to-be-completed nationwide implementation is the ultimate responsibility and governmental authority mission of MSB. This stage involves crude, regional computations of factors of safety along type sections of inhabited areas based on *what is already known* about slope geometry, soil distribution and soil properties (shear strengths, pore water pressures, loads etc.). Results are used to assess and map levels of mass movement hazard in accordance with soil- and slope-specific recommendations for levels of factors of safety, and, to subsequently analyse the need for any potential implementation of investigation stage two. This stage is referred to as "*the detailed investigation stage*" and is the responsibility of the specific landowner and/or the relevant municipality. It requires actual field and laboratory studies so that geometries, shear strengths and pore water pressures within sections found especially vulnerable can be roughly determined. Should results be deemed necessary, studies are further intensified and diversified in accordance with investigation-stage three so that these factors, and their margins of errors, can be decisively determined along a number of potential slip surfaces. Stage four involves *"complementary investigations"* mainly aiming at assessing possibilities, costs and dimensions of potential intervention measures.

As the first formal recognition and incorporation of the mass movement hazard into national social structure planning and development, the slope stability investigation program is and has been fundamental for Swedish mass movement hazard and risk management. However, during recent years, the program has been subject of criticism. Hultén et al. (2005) highlighted the lack of recognition given potential effects of e.g. climate change. Inherited sensitivities of key factors to changes of the natural environment are not much considered whereby it is possible that some of the mapping will have to be redone for the future. Also, the program is delineated based on investigations of slope stability made mainly within the Göta Älv region. Techniques are hence standardised based on investigations of slope stability of clayey slopes prone to rotational sliding, and not straightforwardly adopted to all other national areas potentially at risk.

It should also be noted that stability-mapping measures have as of yet been restricted to inhabited areas. Not yet developed areas thus completely lack hazard assessment, something to bear in mind for the future. Moreover, there is the lack of recognition given actual risks. The consequences of potential mass movements are not a factor considered. Risk analysis is actually something rather novel to Swedish natural hazard management and it is only during recent years that potential methods for implementation and execution have been thoroughly contemplated. SGI and the Chalmers University of Technology conducted pioneering work in the late 1990s. A method for mass movement risk assessment in accordance with a risk matrix, taking into respect four levels of probability of movement on the one hand, and four levels of severity of physical consequences on the other was developed (Alén et al., 2000) (fig. 5c). The method has since been successfully applied to some communities along

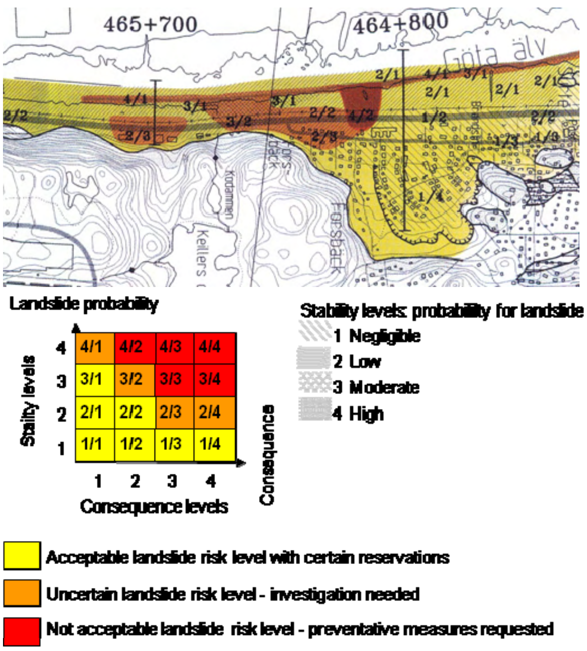


Figure 5c. Example of a mass movement risk map according to the methodology developed by Alén et al. (2000). From Göransson et al. (2009).

the Göta Älv river valley downstream of Lake Vänern. However, it has not been applied to other relevant parts of the country. Risks in terms of associated release and transport of pollutants is not a factor much considered.

With regards to measures of more direct monitoring of factors indicative of potential slope movements, SGI currently has some instruments in place along some areas at risk (e.g. along parts of the Göta Älv and the Ångermanälven river valleys). Related research programs have also been launched during recent years in collaboration with other European states.

6. Soil contamination in Sweden

The following chapter reviews the extent and general character of sites of established/suspected/potential future soil contamination in Sweden. Reasons, legislative responsibilities and management measures are also considered.

6.1. The historical context

Swedish environmental pollution history is largely an account of Swedish industrialisation. Starting in the mid-19th century, the country went from being a relatively poor, agricultural country to a rich and advanced industrialised nation over just a hundred years. The landscape as well as the society underwent a dramatic transition as the country's natural resources were progressively exploited upon. Widespread woodlands were subject of intense forestry, mining activities up north expanded and eventually, glass-, metal-, textile-, electro-, chemical-, petrochemical- and engineering industries spread throughout the country together with an ever-expanding infrastructure. The economy thrived, but the environment gradually deteriorated through the escalating release and accumulation of hazardous and toxic substances in the air, in the water and in the soil. Meanwhile, artificial fertilizers and chemical pesticides were starting to become increasingly common in the remains of the agricultural sector, hence exacerbating the problem. Proper concerns were not raised until the 1960s, at what point in time the industrial era in the country stood at its height, and substantial and in many ways irreversible damage had already been done. Since then, the Swedish government has taken on an increasingly active environmental approach whereby investigations and remediation measures of contaminated soil, as well as control programs of environmentally hazardous activities and their process substances and waste have been standardized, legislated and initiated. Hence, the knowledge about the extent, character and risks of existing and potential sources of soil and overall environmental pollution has increased substantially.

6.2. Extent, distribution and character

As a result of the mandatory nationwide inventory investigations mentioned in the introduction, a little more than 80 000 sites of potential soil contamination have now been identified throughout Sweden (SEPA, 2009a). Due to the fact that most of these investigations have been completed, and based on the fact that this number has not increased significantly over the past few years, it is believed to be a good approximation of the total number of potentially polluted sites within the country (SEPA, 2009a). Adding to this number however, are numerous (several thousands of) facilities classified as hazardous meaning that their ongoing emissions may pollute the air, surface water, groundwater and/or soil (SEPA, 2008a; SEPA, 2008b). With regards to the mass movement-contaminant release and transport hazard, these facilities are of just as big a concern as already contaminated soils. Much in terms of detailed investigations of the potentially contaminated sites identified remains to be done. Still, initial investigations and national registers within which all environmentally hazardous facilities are to record their emissions allow for some theorising on the overall geographical spread, as well as the overall qualitative characteristics of ascertained as well as potential/future sites of soil contamination.

A majority of the potential sites of soil contamination can somehow be related to one or typically several historical and/or present-day industrial activities; either through the more direct emissions (release and/or leaching of pollutants into soils during production), and/or through more indirect emissions stemming from e.g. landfills of process waste (SEPA, 2009a). Consequently, many of the sites are found in close connection to open waters since the industrial activity/-ies responsible for their existence often have required water for both production and transportation purposes. This is especially true for the more severely polluted areas. Major riverine sites and coastal areas, especially those of major harbors, are hence those areas most severely affected overall.

Nationwide, the most common types of contaminants found are various metals, arsenic, halogenated hydrocarbons, dioxins, PAHs (polycyclic aromatic hydrocarbons), oil, phenols and various organic solvents (SEPA, 2009a; fig. 6a). This is in addition to widespread soil acidification due to (i) traffic fumes, (ii), industrial air pollution and associated fallout and, (iii), agricultural use and hence release of artificial

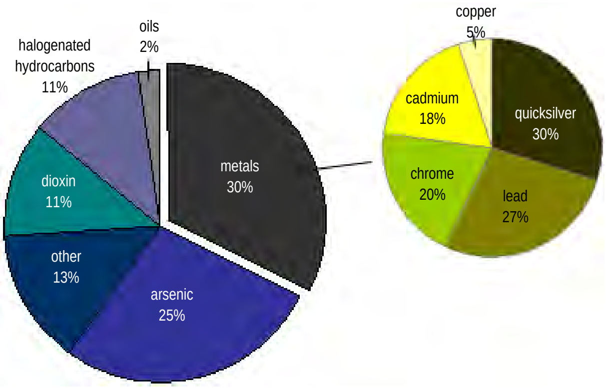


Figure 6a. The most common established and/or suspected types of pollutants at the 216 top-priority sites of soil contamination in Sweden 2008. After SEPA (2009a).

fertilizers and chemical pesticides into the surrounding environment (Andersson, 2009). Due to the fact that investigated sites commonly have suffered contamination from more than one responsible act, pollutants are furthermore often found in highly variable combinations and concentrations. It is thus hard to make generalisations concerning geographical concentration of specific types of pollutants in certain regions based on traditional geographical distribution of specific industrial branches. I.e., at one polluted site, multiples of the above mentioned contaminants are typically found (SEPA, 2009a). This is especially true for southern Sweden, where a great variety of industrial activities have been (and still are being) concentrated (see fig. 6b). Some overruling trends can however be deduced. For example, there is the forest industry which including sawmills, wood impregnation facilities and pulp- and paper manufacturing practices is believed to be responsible for almost one third of all contaminated sites within the country. Although spread throughout many parts of Sweden, such practices and facilities have traditionally been concentrated to areas along the rivers and coasts of the north of the country. Severe dioxin, PAH, oil, phenol and heavy metal pollution has hence followed in many soils within these regions.

Another example is the inorganic chemical, textile and leather industry that is and has been especially prominent in parts of south-western Sweden; mainly in and around Klarälven and the Göta Älv river basin. This has caused substantial release and accumulation of (e.g.) petroleum products, solvents and various metals at many sites there. Mining activities as well as glass-industries are other branches commonly held causative for the contamination of soils. These, however, have normally been restricted to interior parts of Sweden and are not typically found adjacent to open waters. As for the engineering industry (which at present is the largest in Sweden), however, this is an industrial branch that is widespread throughout most parts of southern Sweden hence responsible for much of the enrichment of heavy metals in soils in and around surface water systems there.

Concluding, as a result of widespread industrialisation over more than one hundred and fifty years, sites of potential as well as established soil contamination is now spread throughout as good as all parts of Sweden with the exception of the more pristine, isolated north-western regions. Although there are some patterns to the geographical distribution of certain industrial activities, multiple organic as well as inorganic pollutants are typically found/suspected/to be anticipated at associated sites of soil contamination. This is in addition to extensive soil acidification. Areas most severely affected are those neighbouring major rivers, lakes and harbor areas – mainly in the southern parts of the country. However chaotic, fig. 6b somewhat serves to demonstrate the overall geographic distribution and complexity of Swedish industrial activities, environmentally hazardous facilities and potential associated sites of soil contamination.

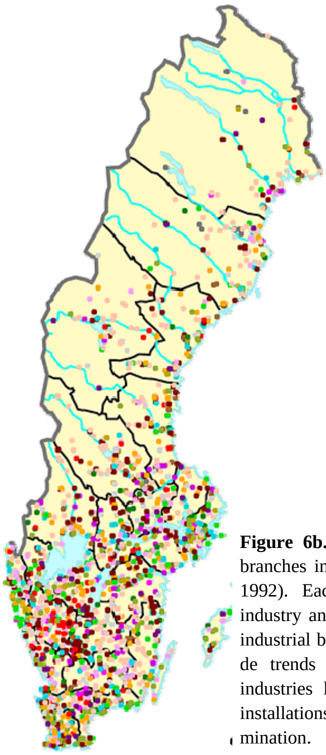


Figure 6b. A map of dominating industrial branches in Sweden 1993 (Wastenson et al., 1992). Each dot represents a dominating industry and each color represents a specific industrial branch. Demonstrative of nationwide trends in distribution and variation of industries hence environmentally hazardous installations and sites of potential soil contamination.

6.3. Responsibilities and management

Swedish environmental law rests upon the Environmental Code (Miljöbalken) of 1999 within which overarching responsibilities and rules of consideration concerning the sustainable safeguarding of the Swedish environment are formulated and legislated. As such, it is the most important and powerful piece of legislation when it comes to responsibility matters relating to established and/or potential cases of soil contamination. Two of the most fundamental principles declared are

- the polluter pays principle, and,
- the precautionary principle.

This basically means that for any environmentally hazardous activity, it is the operator who is responsible for seeing to that necessary mitigation measures are undertaken and made official before, during and after any potential environmental influence. However, as with concerns of mass movement hazards, there are governmental authority missions, bodies, hierarchies and contribution systems implemented so as to identify, enforce, guide and support relevant and in some cases defined and legislated mitigation measures.

6.3.1. Contaminated soil

Of the sixteen environmental quality objectives set up and put into practice by the Swedish Parliament (in between 1999 and 2005 as mentioned in the introduction), number four – *"a non-toxic environment"* – deals especially with aims, actions and responsibilities concerning soil contamination. The overall vision of this objective is a Swedish environment free from "*man-made or extracted compounds and metals that represent a threat to human health or biological diversity*" (SEPA, 2009b). Concerning sites of potential soil contamination specifically, it is said that *"appropriate action will have been taken by the end of 2010 at all contaminated sites that pose an acute risk on direct exposure, and at contaminated sites that threaten important water sources or valuable natural environments, today or in the near future*", and, that "*between 2005 and 2010, measures will be implemented at a sufficiently large portion of the prioritized contaminated sites to ensure that the environmental problem as a whole can be solved by 2050 at the latest"*. This is according to interim targets number six and seven respectively (SEPA, 2009a).

In order to be able to meet these objectives, the governmental agency appointed overall responsible for their fulfilment - the Swedish Chemicals Agency (Kemikalieinspektionen) - urged the standardized, nationwide inventory investigations of potential sites of soil contamination mentioned earlier. These investigations can be divided into two main stages namely (i) the identification stage and, (ii), the environmental risk assessment stage. The latter is to be done in accordance with the so-called MIFO (*Metodik För Inventering av Förorenade Områden*)-method which was delineated by SEPA in the late 1990s (SEPA, 1999). The MIFO-method (fig. 6c) takes five main assessment criteria into consideration when evaluating the environmental risks associated with the identified site namely:

- degree of hazard based on toxicity (F),
- level of pollution based on concentrations, volumes and/or areas (N),
- level of sensitivity based on potential human/ environmental exposure (K),
- worth of protection based on protective value of the surrounding environment (S), and,
- spreading conditions.

The assessment results in the site being classified as a class 1 (very great risk), class 2 (great risk), class 3 (moderate risk) or class 4 (slight risk) object. MIFO-investigations can be carried out in two stages depending on need. Resultant risk-levels are used to prioritise and coordinate potential remediation measures deemed necessary.

In accordance with the polluter pays-principle, the ultimate responsibility for the execution and costs of a MIFO-investigation as well as any potential remedia-

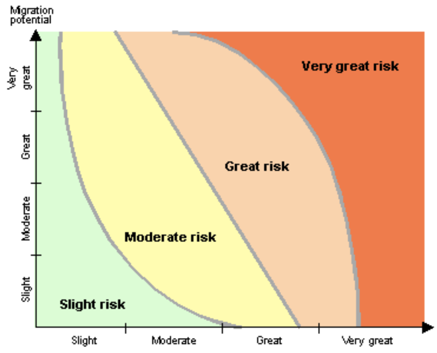


Figure 6c. The MIFO-method risk classification scheme (SEPA, 1999).

tion measure found necessary at the particular site lies with the responsible operator and/or specific landowner. However, documentation, prioritisation, coordination and supervision of the same are mainly concerns of the specific municipality and County Administrative Board (Länsstyrelse). Furthermore, governmental subsidies and overarching supervision is a matter of the Swedish Environmental Protection Agency. The SGI and the SGU are appointed governmental expert agencies in this context.

As already stated, most sites of potential soil contamination within the country are considered identified. However, MIFO-assessments, as well as subsequent after-treatment measures, largely remain to be done. With regards to the interim targets cited above, it is generally believed that whereas number six will probably not be able to be met. Number seven, however, is still considered manageable – knowledge and resources allowing (SEPA, 2009a).

6.3.2. Environmentally hazardous facilities

According to the Integrated Pollution Prevention and Control (IPPC) Directive and chapter 9 of the Swedish Environmental Code, all environmentally hazardous facilities within the country require a permission of operation. Such a permit requires the completion and approval of an environmental impact assessment wherein potential environmental influences and risks, alternative measures of conduct and necessary mitigation/remediation measures are analysed, weighted against one and another and presented for a licensing and supervisory authority (typically the appropriate County Administrative Board). Should a permit be given, chapter 26 of the Swedish Environmental code dictates that for this permission to be retained, annual reports of emissions are to be reported to and approved by specified regulatory bodies (typically the licensing authority) in accordance with the European Pollutant Release and Transfer Register (E-PRTR)-regulation of 2006 when applicable.

7. Combining the hazards: hazard analyses and case studies

With regards to all of the above, it would appear as though the hypothesised mass movement-contaminant release and transport hazard exists throughout much of the country. In the text that follows, specific surface water systems potentially at risk are highlighted. Three risk areas are further analysed based on a weighted assessment of mass movement activity on the one hand, and geographical distribution of environmentally hazardous facilities and potential/established sites of soil contamination on the other. Next, specific risks are demonstrated through a review of consequences of relevant mass movement events as found during this study. Accordingly, the actual extent and character of the potential hazard can be further deduced.

7.1. Areas affected/areas at risk

Of the 393 events recorded and classified according to the standards of Varnes (1978) in the proposition of the national mass movement database, 375 (~95%) have occurred into/in close proximity to surface water systems. The vast majority, 90%, has primarily affected running waters, 5% has taken place into lakes/ponds and the remaining 5% has occurred in and along coastal areas. Fig. 7a summarises those areas most affected (all rivers).

As already noted, one can conclude that the Göta Älv river basin downstream Lake Vänern represents the by far most mass movement-frequented area in Sweden. Since the area is also suffering from widespread soil contamination and a very high concentration of various environmentally hazardous facilities, and since the river serves as the main freshwater resource for approximately 700 000 people, it ought to be considered the prime risk area in terms of potential pollution release and transport in connection to mass movement activity. However, since this is also the area so far most acknowledged in this context, it will not be the main focus of this study. Instead, the reader is referred to the work of Göransson et al. (2009) for further information on risks within this region specifically.

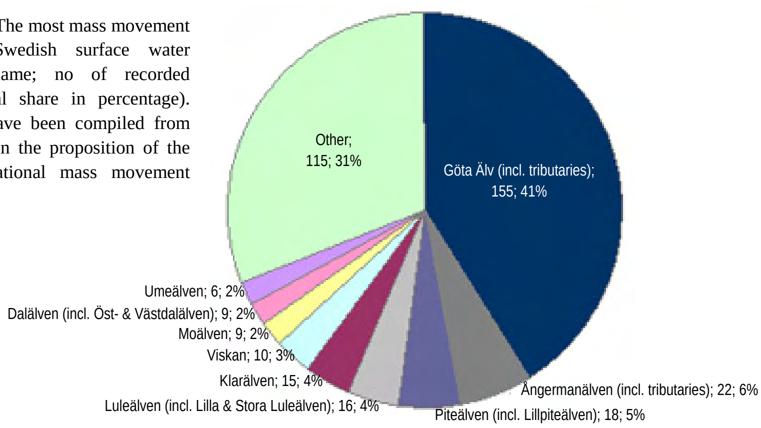


Figure 7a. The most mass movement -affected Swedish surface water systems (name; no of recorded events; total share in percentage). Numbers have been compiled from recordings in the proposition of the Swedish national mass movement database.

Figure 7b. Viskan, Klarälven and Ångermanälven: the three SWS chosen for more detailed risk analysis (base map ©Lantmäteriet, 2009). Circled areas indicate the location of the specific reaches subject of study.

Based on remaining SWS at risk as indicated by fig 7a, three (i.e. parts of three) have been chosen for more detailed hazard analysis; *Viskan*, *Klarälven* and *Ångermanälven*. The respective location of these three rivers, and the respective specific reaches subject of analysis, is illustrated in fig. 7b.

Except for their respective mass movement-frequency, the three were chosen based on their *dissimilarity* in terms of geology, geography, anthropological influence and type of mass movement activity. This in order to enable comparison and a more complete assessment of nationwide hazards and risks. Amount of relevant information available was another decisive factor.

7.1.1. Viskan

Viskan is the most northerly of the four so-called Swedish west-coast streams. It is approximately 140 kilometres long and has a catchment area of about 2 200 km^2 of which a majority - roughly 60% - is forested (Marks Kommun, 2008). The stream dewaters parts of the south-Swedish highlands as it originates in Lake Tolken in the county of Västra Götaland. From there, Viskan flows WSW in a relatively narrow and in places steep channel through a partly rocky, partly forested, partly open landscape. Eventually, it reaches the city of Borås (63 500 inhabitants) where several old textile factories border its way. Further south, Viskan enters flatter and more low-lying terrain characterised by extensive wetlands and increasingly cultivated areas whereby it gradually calms down, widens and develops distinct meanders. Viskan flows into the Kattegatt Sea through Klosterfjorden some 15 kilometres

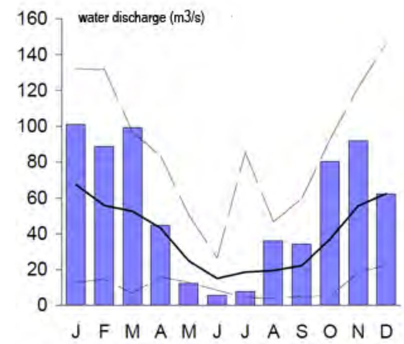


Figure 7c. Mean monthly water discharge (column bars) at Åsbro, Viskan. Normal discharge 1978-2007 is indicated by the solid line. Maximum and minimum mean monthly discharge for the same period is indicated by the dotted lines. From Olofsson (2009).

north of the city of Varberg (26 000 inhabitants). The average annual water discharge is about 34 m^3/s with maximum rates of up to about 180 m^3/s occurring during spring and/or autumn floods, and minimum rates of just a few m^3/s being normal throughout the summer months (Olofsson, 2009) (fig. 7c).

Viskan is arguably one of the most severely degraded SWS in Sweden. Not only does it flow through one of the nationally most densely populated areas with multiple major industries having bordered its way for more than a century thereby causing extensive and oftentimes severe pollution of surrounding media. Lake lowering and -regulation, damming and draining has also been undertaken. Nevertheless, much of the stream course remains of great conservation value with extensive natural pastures and nationally significant salmon- and trout-nurseries and playgrounds along its way.

The studied reaches are located along an approximately 15 km long stretch of the stream located within Mark Municipality in the county of Västra Götaland. Erosion and gullying along the stream course is extensive here and stability enhancement measures have been undertaken. According to the national mass movement database, ten earth/debris slides have occurred within the municipality in connection to Viskan since the 18th century (nine since the 20th century). This makes it one of the most hazardous regions in Sweden with regards to slope failure. All of the more recent recorded events have been about 20-40 m wide and 30-60 m long, however, there is one event on record from the 18th century that supposedly affected a 150*250 m area.

The local geology can in many ways be compared to that of the southern parts of the Göta Älv river valley. According to geotechnical investigations conducted in connection to local slope stability investigations, massive, up to 80-90 m thick glacial and post-glacial clay deposits with interbeddings of coarser and/or organic material dominate the sediments along the stream course (Kristensson, 2000). These are normally overlain by a few metres of recent to contemporary river deposits; i.e. silts and sands. Kristensson (2000) also noted a tendency for the sensitivity of the clays, together with hydrostatic pressures within the soils, to increase towards the south of the region. Quick-clay has been confirmed in conjunction to some of the mass movements recorded in the database. Topographically, primarily along the northernmost parts of the studied section, it is not uncommon with 15-25 metres relief between the top of the riverbank and the deepest parts of the stream (Kristensson, 2000).

The mass movement-contaminant release and transport hazard is illustrated in fig. 7d. The analysis has been restricted to those parts along the stream that have been subject of standardised stability investigations. One environmentally hazardous facility and 21 sites of potential/established soil contamination that lie within (i) 150 metres distance of the river course (the maximum extent of earlier experienced movements) and, (ii), stability zone 1 or 2 were identified (table 7i). A full inventory of these objects can be found in appendix 1a.

The single identified environmentally hazardous facility and 13 of the 21 identified sites of potential soil contamination were found to lie within stability zone 1 and are hence located in areas at direct risk of slope failure. Of the 13 sites of potential soil contamination within stability zone 1 in turn, four have been subject of more detailed MIFO-investigations. Two of these sites have been remediated.

		Sites of potential/established soil contamination: MIFO-class					Environmentally hazardous facilities	
		1	2	3	4	n.d.		
stability zone	1		1	2	1	9	1	**14**
	2					8		**8**
			1	**2**	**1**	**17**	**1**	**22**

Table 7i. A summary of identified risk objects (Viskan) and their location with respect to defined stability zones.

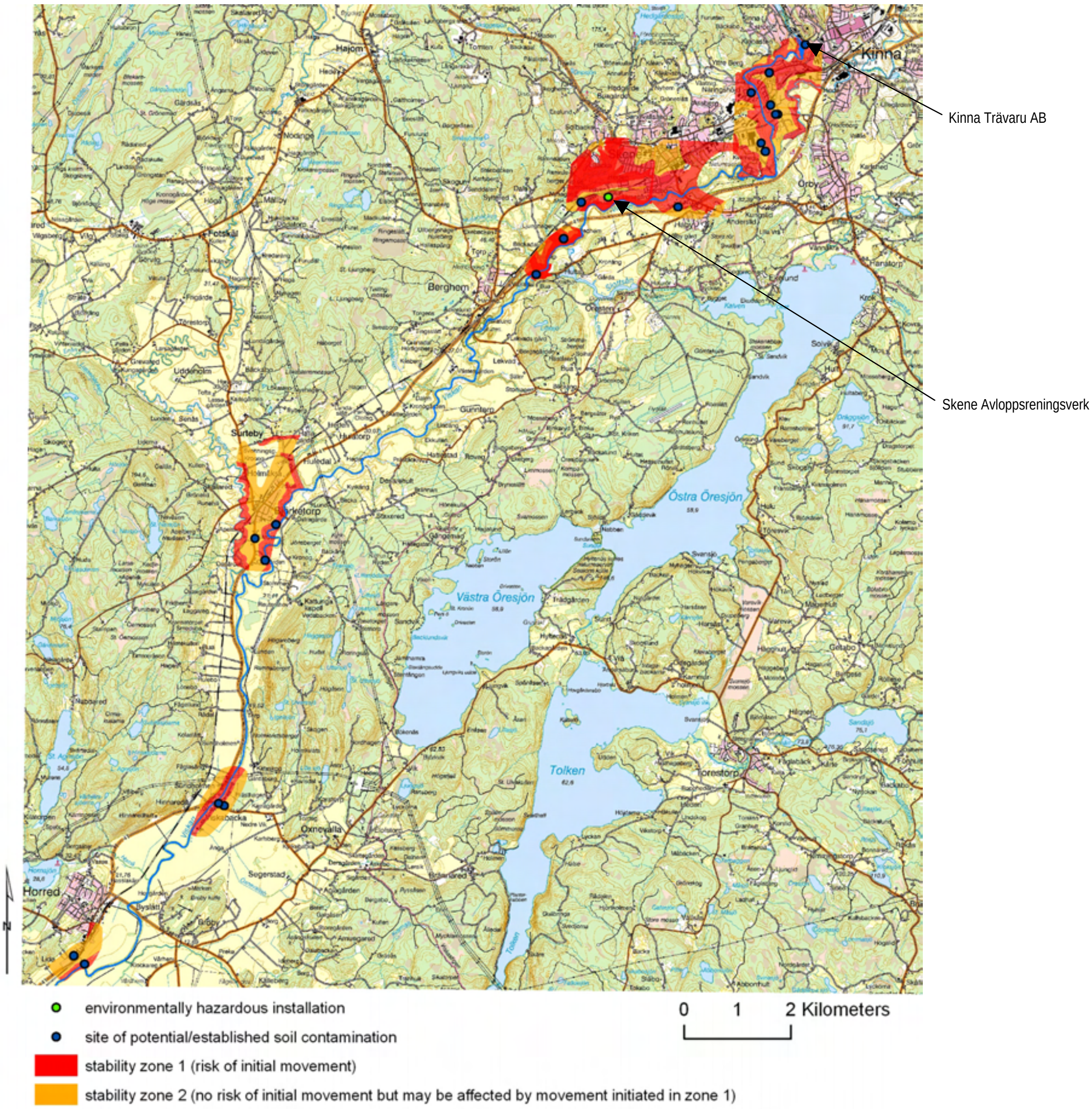


Figure 7d. Environmentally hazardous facilities and sites of potential/established soil contamination within areas at risk of mass movement hazard along Viskan in Mark Municipality. Base map ©Lantmäteriet (2009). Geographic information on stability zones from Mark Municipality (2009). Geographic information on environmentally hazardous facilities/sites of potential/established soil contamination from the County Administrative Board of Västra Götaland (2009a, b).

The following risk objects may be highlighted:

- **Skene Avloppsreningsverk.** A municipal wastewater treatment plant located within stability zone 1 (clay/si/sa on clay). Listed both as an environmentally hazardous facility and as a site of potential soil contamination. According to a study conducted by the County Administrative Board of Västra Götaland (2002), the sewage sludge of this plant contains elevated levels of dioxin and Sb (in addition to expected nitrogen). The reason for this is believed to be an upstream textile industry. In total, roughly 17 200 people are connected.

- **Kinna Trävaru AB.** A closed timber trading facility wherein impregnated wood was handled and stored between 1930-99. The site is located within stability zone 1 (si/sa on clay), in direct connection to Viskan. Investigations have indicated As- and PAH-soil contamination and the risk of spread of contaminants into Viskan has been deemed as very high. The object has been classified as a MIFO class 2-object.

7.1.2. Klarälven

Klarälven is arguably the most southerly of the major rivers of Scandinavia. Originating in Lake Rogen in the county of Härjedalen, Sweden, the river takes a detour into Norway before entering Sweden yet again in northern Värmland. From there, it follows a bedrock graben and flows SSE following impressive meanders over about 90 kilometres before reaching Lake Vänern - the largest freshwater lake in Sweden - with a delta upon which the regional capital of Karlstad (56 000 inhabitants) is located. The entire length of the river is estimated at 460 kilometres and the catchment area is approximated at 11 820 km^2 (Nationalencyklopedin [NE], 2009a).

The northernmost part of the Klarälven river course is characterised by mountainous terrain. Much of the catchment area located further south however – i.e. the regions located within Värmland – consists mainly of extensive forested areas, some cultivated grounds and some open lands. The lowermost part of the river - the delta - is, where not built upon, characterised by a mosaic of different types of vegetation and hence ecosystems which have resulted in the area being classified as one of national environmental conservation interest.

Klarälven has an average annual water discharge of about 165 m^3/s, however, seasonal variations are considerable with winter lows of 17 m^3/s and spring highs of 1 700 m^3/s (Karlstad Kommun, 2009). Precipitation and snowmelt are the two most important factors with spring flood typically occurring twice; once in April in connection to snowmelt in the southernmore parts of the river valley proper, and once in May in connection to snowmelt in the northernmore, mountainous catchment area. Sediment-transport capacities as well as geochemical features have been shown to vary accordingly (Sundborg, 1973; fig. 7e). There are eight hydroelectric power plants along the river course yet no major water reservoirs (NE, 2009a).

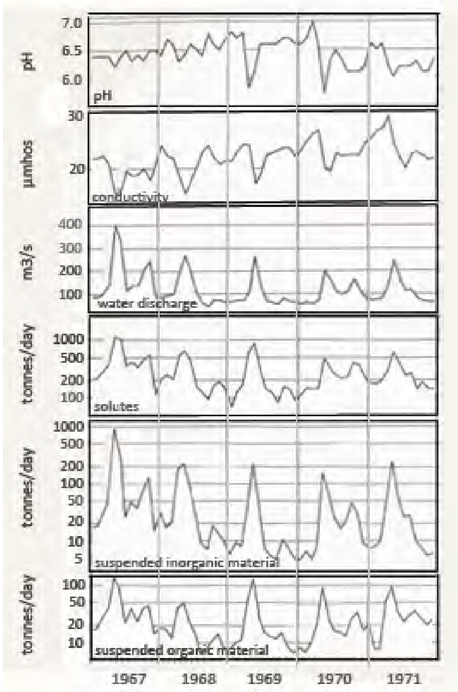


Figure 7e. Diagram of daily averages of pH, conductivity, discharge and transported solutes, suspended organic and inorganic material for Klarälven. Translated from Sundborg (1973).

In spite of its relatively southerly and interior location, Klarälven has a geology and geomorphology that in many ways are more comparable to the rivers of the far north. Most of the course of the river - the entire reach studied here - lies well below the highest shoreline and has hence evolved mainly in accordance with the deglaciation processes of the past ten thousand years. Considerable isostatic uplift, still occurring at a local rate of about 3.5 mm/yr, has been the overall dominant agent of change, causing almost incessant incision through gradual tilting of the river course towards the south. As a result, a sequence of down-cut river deposits and delta sequences have come to form towards the river's present-day debouchment in Lake Vänern (SGU, 2000). In places, downcutting has been so intense that steep, up to ~20 m high river banks have formed. In reaches of less relief, recent river deposits are common.

A typical geological sequence for the here highlighted more southern parts of Klarälven is demonstrated in fig. 7f. The figure is an illustration of a local drillcore that was examined in conjunction with regional geological surveys by SGU (2000). Three generations of sediments were distinguished:

- the oldest, lowermost *glacial* deposits described as coarse clays with some interbeddings of pervious layers of silt and/or sand,
- the subsequent *postglacial* deposits consisting typically of 5-10 m of fine-grained, homogenous clays, and,
- the most *recent* river deposits, mainly silts and sands with varying organic content.

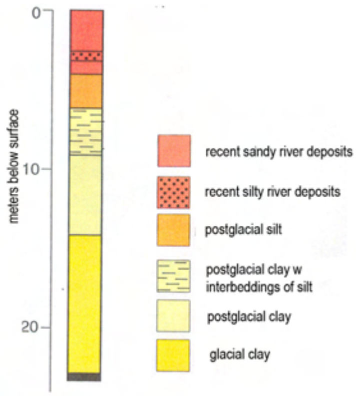


Figure 7f. A layer sequence from a drill core at Våxnäs near Klarälven, Värmland illustrating the geological conditions in the here studied area. Translated from SGU (2000).

		Sites of potential/established soil contamination: MIFO-class					Environmentally hazardous facilities	
		1	2	3	4	n.d.		
stability zone	1		4	6	1	2	2	**15**
	2	2	4	10	6	1	7	**30**
		2	**8**	**16**	**7**	**3**	**9**	**45**

Table 7ii. A summary of identified risk objects (Klarälven) and their location with respect to defined stability zones.

Mass movements in the form of slides, falls and flows have historically been relatively common along Klarälven, especially so along the more vulnerable high relief reaches where bank erosion is, and has been, most prominent. Of those most affected SWS as found during this study, Klarälven ranks as no 5 with 4% of the events. The most common types of movements are comparatively minor earth falls over one or a couple of thousand square metres. However, bigger events involving the displacement of ten to fifteen thousand square metres have been documented on several occasions. Examples are the 1934 earth slide near Vålberg involving the displacement of 10 000 m^3, and the 1983 Bengtsbol earth slide through which some 15 000 m^3 was set into motion. These larger movements have typically involved a certain degree of sliding and/or flowing. Quick-clay and artesian groundwater has commonly been found associated. Silt is the overall dominating fraction involved, followed by clays and fine-grained sands.

Fig. 7g illustrates the mass movement-contaminant release and transport hazard for the southernmost parts of Klarälven. Along this approximately 20 km long stretch, there are nine environmentally hazardous facilities and 36 sites of potential/established soil contamination that lie within (i) 350 metres distance of the river course (the maximum extent of earlier experienced movements) and, (ii), either stability zone 1 or 2 (table 7ii). A full inventory of the specific risk objects can be found in appendix 1b.

Of the nine environmentally hazardous facilities, two lie within stability zone 1 and are hence located within areas at direct risk of slope failure. Of the 36 sites of potential/established soil contamination, the corresponding number is 13. Of those 13 in turn, eleven have been classified according to the MIFO-method. There is a marked overrepresentation of dry cleaning facilities amongst those deemed/suspected responsible. None of the eleven classified zone 1-risk objects have been classified as MIFO class 1-objects. Three objects have been remediated.
The following risk objects may be highlighted:

- **Bycosin/Bycotest AB**. Listed both as an environmentally hazardous facility and a site of soil contamination. Organic chemical industrial activities involving manufacturing and handling of a range of potentially environmentally deteriorating substances - e.g. hydrocarbons, chlorinated solvents, surfactants and heavy metals - have been ongoing on-site since the 1940s. A petrol station has also been located here. Soil contamination has been established (trichloroethylene, metals and approx. 20 tons of hydrocarbons) and leaching indicated. The site is located within stability zone 1 (clay), in direct connection to Klarälven.

- **Klaraviks Tricotfabrik.** A former textile industry/dry cleaning facility active approximately 1890-1980, listed as a MIFO class 2-object. No detailed analyses have been conducted. However, based on historical documentation, moderate to high levels of oil-, PAH-, dioxine- and chloroethylene-contamination is suspected over an approximately 3 300 m^2 area located within stability zone 1 (silt/sand). Since the area is in direct contact with Klarälven, and since wastewater from earlier processes have been directly released into the river, additional volumes of channel bed sediments may also be polluted.

- **Johanssons Kemiska Tvätt.** A MIFO class 2-object of about 870 m^2 located within stability zone 1 (sand), partially steeply inclined towards Klarälven (20 -30 m away). A dry cleaning facility was active here from 1940 until the early -60s and although no detailed analyses have been undertaken, high levels of trichloroethylene-contamination of soil and groundwater is suspected.

- **Branza, Sågverksgatan.** A former accumulator industry at which lead (battery) recycling and refining was undertaken during approximately ten years, starting in the late 1950s. Based on what is known about the processes undertaken when active, and based on measurements of air pollution undertaken in connection to a contemporary sister company, high levels of Pb- and Sb-contamination of the soil within an approx. 4 100 m^2 large area is suspected. The site is located within stability zone 1 (clay), at a distance of 20-30 m from Klarälven and has been classified as a MIFO class 2-object.

- Lindgrens Läderfabrik. A former tannery, active ~1866-1940. During the years 1906-1940, chrome was applied during the tanning process whereby there are now substantiated suspicions of high levels of (primarily) Cr (III, IV)-contamination of both soil and groundwater within (at least) an about 5 800 m^2 area located within stability zone 1 (clay). Since wastewater from the industry was released into Klarälven (about 25 m away), channel bed sediments may also be polluted. The site is rated a MIFO class 2-object.

7.1.3. Ångermanälven

Ångermanälven originates far north in Sweden, in the wild mountainous regions of southern Lappland, close to the Norwegian border. From there, it follows a regional bedrock shear zone and flows SE for about 460 kilometres throughout as good as the entire width of the country, meandering through dense coniferous forests and an increasingly inhabited, anthropologically affected and altered environment. Ångermanälven debouches into the Gulf of Bothnia just north of the city Härnösand (18 000 inhabitants). Natural values along much of the river course are major.

With a total catchment area of about 31 900 km^2, Ångermanälven ranks as the third largest river in Sweden (NE, 2009b). The average annual water discharge

Figure 7g. Environmentally hazardous facilities and sites of potential/established soil contamination within areas at risk of mass movement hazard along Klarälven. Base map ©Lantmäteriet (2009). Geographic information on stability zones/environmentally hazardous facilities/sites of potential/established soil contamination from the County Administrative Board of Värmland (2009a).

is about 525 m^3/s, though this number varies greatly during any given year. Maximum discharge rates occur during spring/summer in connection to snowmelt and may reach heights of about 2 500 m^3/s (potentially up to 4 000 m^3/s in a natural, unregulated state) (Bergström, 1999). Minimum rates during winter may on the other hand be as low as 100 m^3/s. The river has been increasingly regulated sine the 1930s and there are 39 hydroelectric power plants along the river course (NE, 2009b). Together, these generate approximately 17% of the national hydroelectric power production.

The studied section is located along a southerly part of the river course, along an approximately 20 km long stretch of the river located within the municipality of Kramfors in the county of Västernorrland. Here, the river proper displays into a high-relief fjord landscape of steep, deep valleys shaped through repeated glaciation and deglaciation processes. Isostatic uplift following the most recent of these coupled events is still major. The highest shoreline is regionally located about 285 m.a.s.l., and the current local uplift rate of about 8 mm/yr represents one of the highest in the country (Viberg et al., 1989).

Elevated rock outcrops are relatively common here, however, it is the thick (40-60 m) deep sedimentary deposits within the valley proper that typifies the geology of the area and makes it one of the most mass movement-prone regions in Sweden. A typical, schematic cross-section and geological sequence of the river course along the studied area is demonstrated in fig. 7h (from Fredén, 1996). Three generations of fine-grained deposits are distinguished between, namely:

- the *glacial deposits* which are locally characterised by silt, silt with interbeddings of clay and varved clay with the overall clay-content increasing with distance from the highest coastline (i.e. with increasing depth of deposition),
- the *postglacial deposits*; typically redeposited silts and clays, and,
- the (recent) *river deposits*; mainly sands and silts (Fredén, 1996).

It is the post-glacial deposits, also known as *Ådalslerorna*, that have been shown to pose the greatest mass movement hazard (Viberg et al., 1989). The shear strength of those deposits varies remarkably with quick-clay occurring in places. Natural leaching processes and likewise natural pressure-gradient changes combined with especially high sulphidic-/organic content are believed to be primarily responsible through gradually decreasing the mechanical shear strength of the sediments with time.

Considering *types* of mass movement activity, earth falls and especially earth slides are those most common here. Shoreline erosion is intense along much of the studied reach and in places, smaller movements occur relatively frequently. Larger events have so far been relatively uncommon but they do occur. As an example, in 1959, a 600 m long stretch of land along the bay Kyrkviken was subject of a retrogressive earth slide whereby slide-masses were transported at least 700 metres along the bottom of the river into the deepest parts of the valley (Jerbo & Sandegren, 1963). Quick-clay was found at the site of movement during subsequent investigations.

The mass movement-contaminant release and transport hazard is illustrated in fig. 7i. Along this ~20 km long reach, there are seven environmentally hazardous facilities and 28 sites of potential/established soil contamination that lie within (i) 100 metres distance of the river course (the maximum extent of earlier experienced mass movements) and, (ii), stability zone 1 or 2 (table 7iii). The hazard analysis has constrainedly been restricted to stability-mapped areas. A full inventory of identified risk objects can be found in appendix 1c.

Of the seven identified environmentally hazardous facilities, two lie within stability zone 1 and are hence located in areas at direct risk of failure. The corresponding number for the indentified sites of potential soil contamination is 13. Only three of those have been classified according to the MIFO-method. There is a marked overrepresentation of sawmills and landfills amongst those facilities deemed responsible for the potential pollution.

	Sites of potential/established soil contamination: MIFO-class					Environmentally hazardous facilities	
	1	2	3	4	n.d.		
1	1			2	10	2	**15**
2		1		2	12	5	**20**
	1	**1**		**4**	**22**	**7**	**35**

Table 7iii. A summary of identified risk objects (Ångermanälven) and their location with respect to defined stability zones. Please note that Kramforsviken has been placed in the "zone 1-box" even though parts of this object are located within zone 2 (see text).

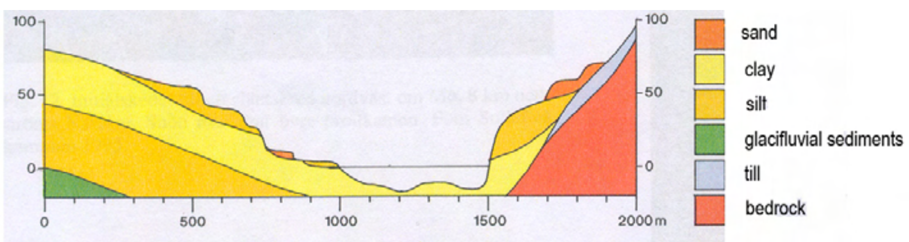


Figure 7h. A schematic cross section of the southernmore parts of Ångermanälven representative of the area subject of risk analysis in this study. Translated from Fredén (1996).

The following risk objects/areas may be highlighted:

- Mondi Dynäs AB // Väja Sulfatfabrik / Pappersbruk. Listed both as an environmentally hazardous facility and as a site of potential soil contamination. Between 1965 and the early 1970s, wood impregnation was carried out on-site whereby phenol-contamination of surrounding sediments is plausible (however not determined). Today, Mondi Dynäs AB produces ~200 000 tons of paper on-site yearly. Various potentially environmentally deteriorating substances (e.g. As, Hg, NH_3, NO_x, S, Zn, TOC, NMVOCs) are applied and released throughout the production process (SEPA, 2009c). The site is located within stability zone 1 (clay>1:10), in direct connection to Ångermanälven.

- Bollstasågen. Listed as a site of potential soil contamination and located within stability zone 1 (clay>1:10). Sawmilling has been ongoing here since 1860. Between 1949 and 1968, impregnation was carried out onsite. High levels of Cu- and Cr-contamination and very high levels of As- and creosote-contamination has been established in surrounding soils and sediments. The site neighbours Ångermanälven and there are suspicions of contamination of adjacent river bed sediments as well. Damage on plants and fish has been confirmed.

- Kramforsviken. Although listed as *one* single site of potential soil contamination (MIFO class 1), this is actually an approximately 350 000 m^2 area (a bay) within which multiple potentially environmentally deteriorating activities have been ongoing for more than 120 yrs in more or less direct connection to Ångermanälven. Some parts of the listed area is located within stability zone 1 (clay>1:10), and some within zone 2 (silt/sand on clay<1:10 // silt/sand>1:n). Based on what is known about historical activities, and based on sediment samplings that were undertaken in places during the 1970s, suspected levels of contamination in surrounding structures and groundwater has been estimated as high and corresponding levels of contamination in the surrounding sediments as very high. Suspected contaminants include phenols, Hg, As, Pb, Cd, cyanide, dioxin, PCB, chloroethylene, Cu, Cr, Ni and various petroleum products.

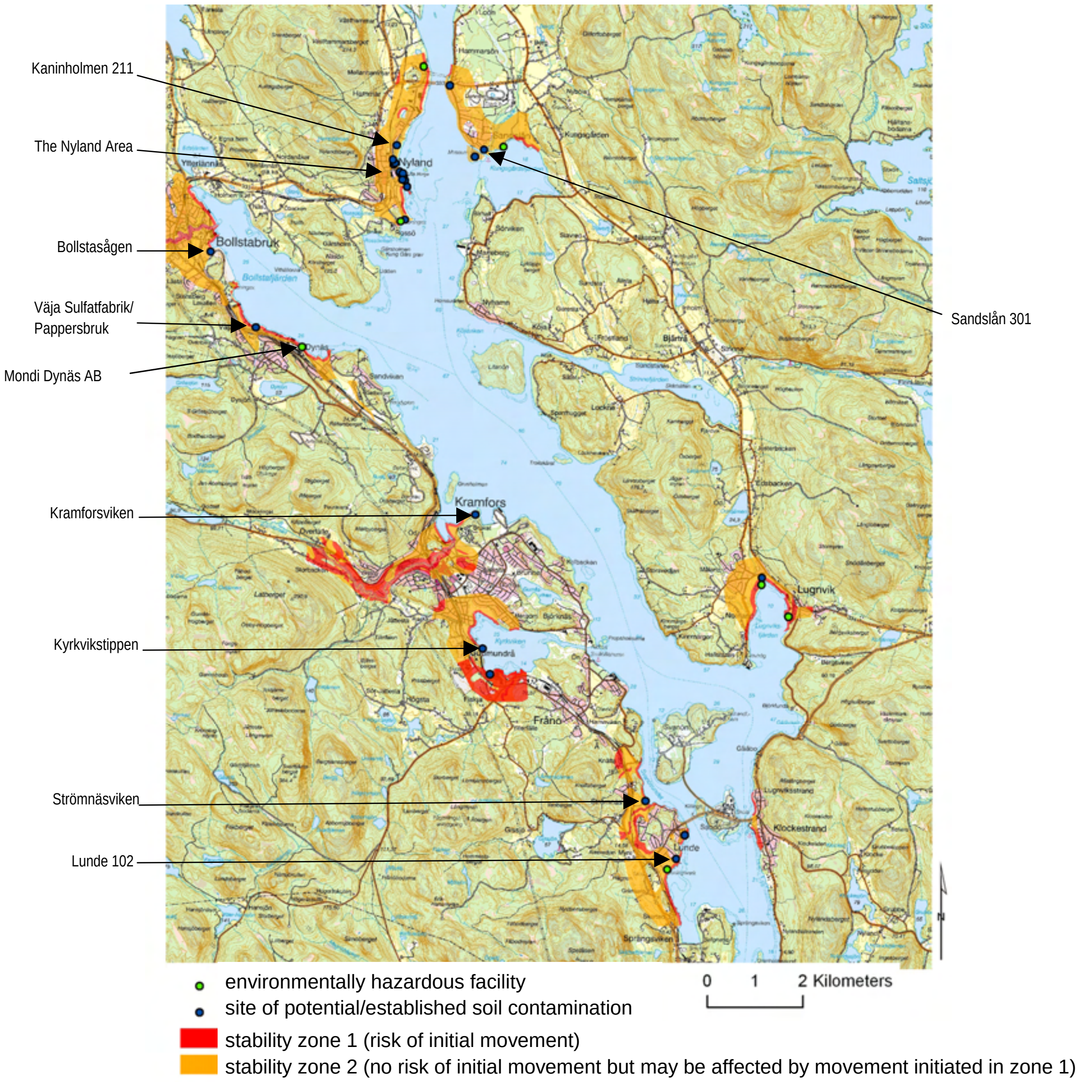


Figure 7i. Environmentally hazardous facilities and sites of potential/established soil contamination within areas at risk of mass movement hazard along Ångermanälven in Kramfors Municipality. Base map ©Lantmäteriet (2009). Geographic information on stability zones from MSB (2007). Geographic Information on environmentally hazardous facilities/sites of potential/established soil contamination from the County Administrative Board of Västernorrland (2009a, b).

- **The Nyland Area.** Within this region there are eight sites of potential soil contamination. None of these risk objects have been classified according to the MIFO-method. A shoe factory, three printing works, two petrol stations, a tier and one car care facility – none of which active – represent the activities supposedly responsible for the potential contamination at these sites respectively.

- **Lunde 102 // Kaninholmen 211 // Strömnäsviken // Kyrkvikstippen // Sandslån 301.** These objects are all closed municipal household/industrial landfills – active during the mid-1900s – that have now been identified as sites of soil contamination. None of the objects have been classified as high risk objects, probably due to their relatively minor extent. However, they serve to demonstrate the historical lack of recognition given the potential mass movement-contaminant release and transport hazard. All of the landfills are located in direct/close connection to Ångermanälven and in some of the cases (Lunde, Kyrkvikstippen) in areas that are steeply inclined towards the river. Parts of the Kaninholmen, Strömnäsviken and Kyrkvikstippen landfills have actually already fallen into the river.

In summary, within the studied areas, 102 risk objects in terms of potential mass movement-contaminant release and -transport have been identified (table 7iv). 85 of these are sites of potential/established soil contamination, 17 are environmentally hazardous facilities. 44 lie within stability zone 1 and are thus at direct risk of slope failure. 58 lie within stability zone 2 and may hence be affected by the potential landward extension of a mass movement triggered within adjacent zone 1.

Of the 85 sites of potential/established soil contamination, 43 have been assessed with regards to environmental risk in accordance with the MIFO-method. Only three have been classified as class 1-objects of which two lie within stability zone 2. Five have been fully remediated.

It should be stressed that the studied areas jointly merely make up for a *very* small proportion of the total length of Swedish SWS shorelines susceptible to mass movement hazard. The number of *national* risk objects is hence bound to be in the range of several thousands. It is furthermore worth noticing that there - as expected - appears to be a certain geographical zonation of present-day/historical industrial activities and thus established/potential types of contaminants (e.g. sawmills for Ångermanälven, dry cleaning facilities for Klarälven). Likewise, there are certain risk objects that are present within all of the studied areas; e.g. wastewater treatment plants, municipal and industrial landfills and petrol stations.

Last but not least, it is interesting to note that of the 44 (18 MIFO-classified) objects located within stability zone 1, only one has been classified as a class 1-object.

		Sites of potential/established soil contamination: MIFO-class					Environmentally hazardous facilities	
		1	2	3	4	n.d.		
stability zone	1	1	5	8	4	21	5	**44**
	2	2	5	10	8	21	12	**58**
		3	**10**	**18**	**12**	**42**	**17**	**102**

Table 7iv. A summary of identified risk objects (total: Viskan, Klarälven, Ångermanälven) and their location with respect to defined stability zones.

7.2. Historical experiences

A full review of those mass movements that during this study have been found to have affected one or many SWS *and for which those effects have been further documented* can be found in the table in appendix 2. Below follows more elaborate case studies for six of those events. In addition to amount and type of documentation, these six sites have been chosen based on their respective dissimilarities in geography, geology, type of movement and – most importantly – type of effects noted. A summary of those respective characteristics can be found in table 7v in the end of this subchapter. Geographical locations are shown in fig. 7j.

Jointly, the six case studies should form a good basis for further discussion on actual risks, key process and properties.

Figure 7j. Approximate locations of the six mass movements reviewed in the text (base map ©Lantmäteriet, 2009).

7.2.1. Tångböle, Jämtland

During the spring of 1995, following extreme amounts of runoff due to an extraordinary and prolonged spring flood, two major earth slides occurred along an approximately 300 m long stretch of the river Indalsälven just upstream Lake Gevsjön (Ekberg et al., 1995; fig. 7k). The site of failure was located within steep, forested, 30-40 m high river banks made up of silt and clay. The total volume of displaced material was estimated at about 200 000 m^3.

In a report dated in early September the year of the slide, it was concluded that the movement had caused extensive turbidity with a plume of suspended material being noted as far south as Storsjön, reducing the visibility to a couple of decimetres more than one-hundred kilometres downstream the site of failure (Ekberg et al., 1995). Increases in clay content in the water of private wells as well as in municipal reservoirs were noted all along the way. In places, signs of pollution could also be noted, causing restrictiveness of local supply and usage of freshwater.

Following worries over degrading fisheries in Lake Åresjön, a study by Nilsson (2005) of the lake bottoms of Ånnsjön, Gevsjön, Noren and Åresjön conducted ten years after the Tångböle earth slide(-s) further served to illustrate the full effects of the event. Calculations of rates of sedimentation over the past 80 years then showed substantial increases within all downstream lakes following the occurrence of the slide (Nilsson, 2005; fig. 7l). Maximum increase was - as expected - noted in nearby Lake Gevsjön. There, the rate of sedimentation in the deepest parts of the lake was estimated to have gone from the average 0.015 to 0.095 g/cm^2/yr in the year directly following the slide, a rather instantaneous, more than six-fold increase. In Lake Noren and Lake Åresjön, some 10 respectively 45 kilometres further downstream, similar effects although with a lesser magnitude were also noted up to five years after the event.

Figure 7k. Location (©Lantmäteriet, 2009) and visual (Fredriksson, 1995) of the Tångböle earth slide (-s), Jämtland County 1995.

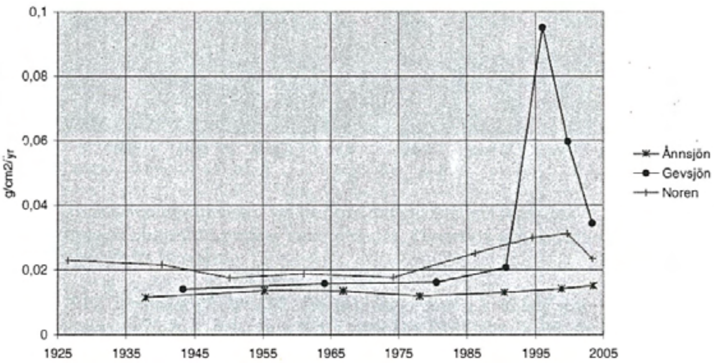


Figure 7l. Sedimentation rates 1925-2005 in lakes Ånnsjön, Gevsjön and Noren located downstream the site of the Tångböle earth slide(-s). Major increases are noted subsequent to the movements. From Nilsson (2005).

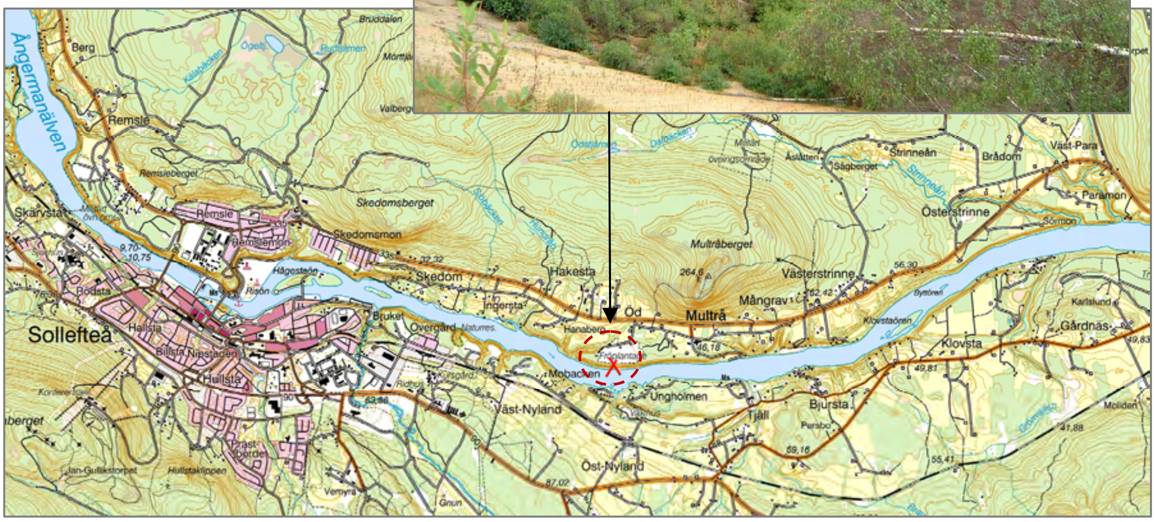
7.2.2. Öd 1, Västernorrland

The Öd 1 earth slide/fall occurred on the 16th of February 2002, along the Ångermanälven river valley a few kilometres downstream the city of Sollefteå (fig. 7m). The translational movement displaced an approximately 95 m long and 10-15 m wide section of a regionally characteristic 40-45 m high, ~30° steep river bank made up mainly of fine sand and silt, a so called *nipa* (Svensson et al. 2006; Fredén, 2002). Some estimated 30-40 000 m^3 of sediments were hence transported into the river along an as good as planar slip surface.

The affected reach had once been used for log dumping. However, at the time of movement, the area served as a seed orchard (Fredén, 2002). Contaminants in the form of fertilizers, pesticides, phenols etc. *might* accordingly have been present in the affected masses yet this was never/has never been confirmed, i.e. analysed further. A single specific cause/trigger for the slide was never concluded upon, however, seasonal thawing and heavy loading of snow were both plausible factors considered (Gullersbo, personal communication, 2009).

The river was covered in ice at the time of the movement, yet, immediate damage was considerable. As the sliding masses moved onto the frozen water surface, the ice was crushed whereby metre-sized blocks were set loose and thrown into the air, up onto the opposite river bank some 300 metres away, crushing both boats and houses there (Gullersbo, personal communication, 2009). Meanwhile, a fan of displaced material formed beneath the site of failure, its spatial extent probably somewhat restricted by the presence of the ice (Svensson et al., 2006). Seven years later, this fan is still in place, virtually unaffected as it has suffered very limited erosion, and is now rather serving as more of a permanent peninsula. It is covered in vegetation and it has permanently altered local flow- and erosion patterns (Svensson et al., 2006).

Figure 7m. Below: location of the Öd 1 slide/fall, Västernorrland County 2002 (©Lantmäteriet, 2009). Right: visual (Svensson et al., 2006) of the displaced material 3.5yrs after the event. Erosion has been very limited.



7.2.3. Trossnäs, Värmland

On the 12th of April 1969, an approximately 350 m long and 150 m wide, half-circular, forested area slid into the regulated Norsälven river some 8 kilometres upstream its debouchment into Lake Vänern (County Administrative Board of Värmland [VL], 1969; fig. 7n). Subsequent investigations classified the movement as a rotational, retrogressive earth slide occurring within thick (15-30 m) deposits of varved, sensitive clays (partially quick clays) overlain by a few metres of sand and silt (SGI, 2009; Lindskog & Wager, 1970). The total volume of involved masses was estimated at some 100 000 m^3, none of which was ever suspected/noted as polluted. Stability computations of the failed bank indicated a former safety factor of just about 1 and so although a single triggering mechanism could never be determined, a combination of long-term traffic-induced erosion, dredging, the sensitivity of the clay, seasonal thawing, and a fortuitous sudden reduction in water-level was jointly considered to have caused the movement (Lindskog & Wager, 1970; VL, 1969). Also, local trenching along the otherwise shallow (3-5 metres) and relatively flat stretch of the river was later indicated through sounding of the affected area, thereby potentially serving to explain the exact point of failure.

During the main movement, which was preceded by almost a full day by local subsidence of the ground surface, the failed parts of the river bank were lowered about 4 metres vertically meanwhile the sliding masses were pushed some 200 metres up- and downstream the river (Lindskog & Wager, 1970). The water depth was consequently reduced by 4-5 metres over a stretch of about 750 metres causing almost complete damming of the river. Since the river was regulated, authorities as soon as possible ordered full stop of discharge in order to prevent further downstream damage through release and transport of failed masses and, in order to enable clearing (VL, 1969). During the following six days, discharge was as low as 7 m^3/s downstream Edsvalla waterworks some ~3.5 kilometres upstream the site of the slide. However, at the 18th of April, the water level upstream the artificial damming had increased to such an extent so that tapping had to be commenced. Over the next 72 hours, water discharge was progressively increased to ultimately 150 m^3/s whereby a new furrow gradually formed within the failed masses. Approximately 25 000 m^3 was hence quickly eroded and transported downstream (Lindskog and Wager, 1970). Flow-rates continued to increase until mid-May reaching as much as 240 m^3/s. Normal discharge of approximately 60 m^3/s was not reached until the end of May.

Figure 7n. Right: location of the Trossnäs earth slide, Värmland County 1969 (©Lantmäteriet, 2009). Above: visual (above; Lindskog and Wager, 1970) demonstrating the extent and immediate effects of the movement. The river has been almost completely dammed by the displaced masses.

Concerning hydrological and environmental effects, initial studies indicated that the main pulse of suspended material arising from the sliding masses following the commencement of tapping moved downstream along Norsälven with an estimated velocity of about 360 m/day (Ehlin & Zachrisson, 1969). Upon reaching Lake Vänern, concurrent circulation patterns were then estimated to have increased this velocity to about 600 m/day. This would explain those extensive effects in terms of alterations in color, temperature and reduction of visibility and light transmission that was noted during later field investigations within the northernmore parts of Lake Vänern. Already in May, such effects were noted as far south as 3 kilometres south of the debouchment of Norsälven (Ehlin & Zachrisson, 1969; fig. 7o). A last tour of inspection along the affected parts of the river was made four months after the slide (i.e. 14/8 1969) at which point in time the narrowing of the furrow was still considerable, alterations in flow- and erosion-patterns were still noted and clay particles from the failed masses were still in suspension several kilometres downstream (Sjöberg, 1969).

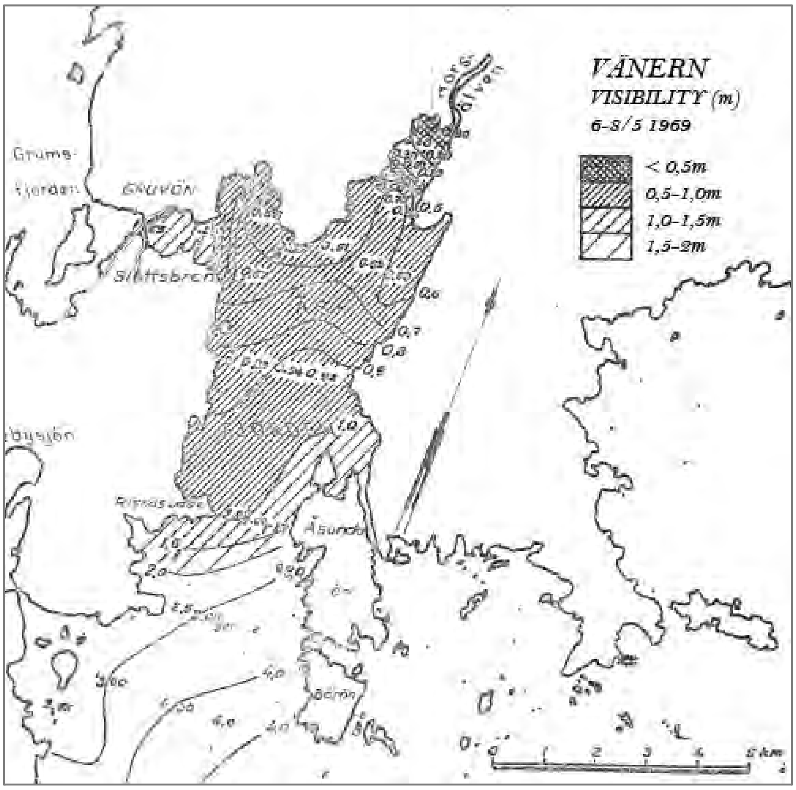


Figure 7o. Reduction in visibility in the northern parts of Lake Vänern as a result of the Trossnäs earth slide. From Ehlin & Zachrisson (1969).

7.2.4. Yara, Östergötland

The Yara earth slide (fig. 7p) is named after the owner of the displaced land surface, namely Yara AB - a producer and supplier of chemical fertilizers. Sometime during the weekend of the 27-28th of October 2007, an earth slide occurred just north of one of their industrial harbor loading terminals, transporting some 1 200 m^2 of landfills and partially contaminated clays into Ståthögaviken near the city of Norrköping, Östergötland (Persson, 2007). As a result, (i) a new bay formed at the site of failure, exposing contaminated masses to the neighboring SWS and, (ii), some 300-500 kg As, 600-1000 kg Pb and Zn and 200-400 kg Cu was transported into the bay (Karlsson, personal communication, 2009; Persson, 2007). Subsequent studies of previously conducted geotechnical investigations of the area indicated that the site of failure had suffered from unfavourable stability conditions with approximately 1 -1.5 m of demolition material from old (sulphuric acid) factories having been placed on top of ~15 m of sensitive clay-deposits in turn overlying some 15 m deep deposits of friction-material (Persson, 2007). Large rainfalls during preceding months, a local drainage dike and increasing traffic(ship)-induced erosion was jointly considered to have triggered the event.

Immediately upon detection of the movement, sounding along the affected stretch of the bay was undertaken. It was then concluded that although the main part of the displaced landfill-masses had been deposited within 20 metres of the original shoreline, much of the affected clays (hence potential particle-bound contaminants) had probably been transported further into the bay (Persson, 2008). A few days later, a second sounding indicated an increase in water-depth along the newly formed shoreline. Two plausible causes were acknowledged: continued soil subsidence of displaced masses and/or continued erosion and transport of the same.

Due to the adverse stability conditions of the quay-area, instant removal of the slide-masses was deemed unsuitable as it potentially would cause further undermining and movement. Instead a silt curtain was installed directly outside and around the main part of the displaced material in order to prevent further spread of contaminants through erosion and leaching (Karlsson, personal communication, 2009). Ensuing sampling of sediments and water in and around the affected area demonstrated that even though overall level of pollution was to be classified as moderate to low according to SEPA-standards, concentrations of solute metals (mainly Cd and Zn which are both relatively soluble metals) within the water inside the silt curtain were generally substantially higher than those outside (Lundgren et al., 2008). Further follow-up studies have been undertaken, however, results have not been made official (Karlsson, personal communication, 2009).

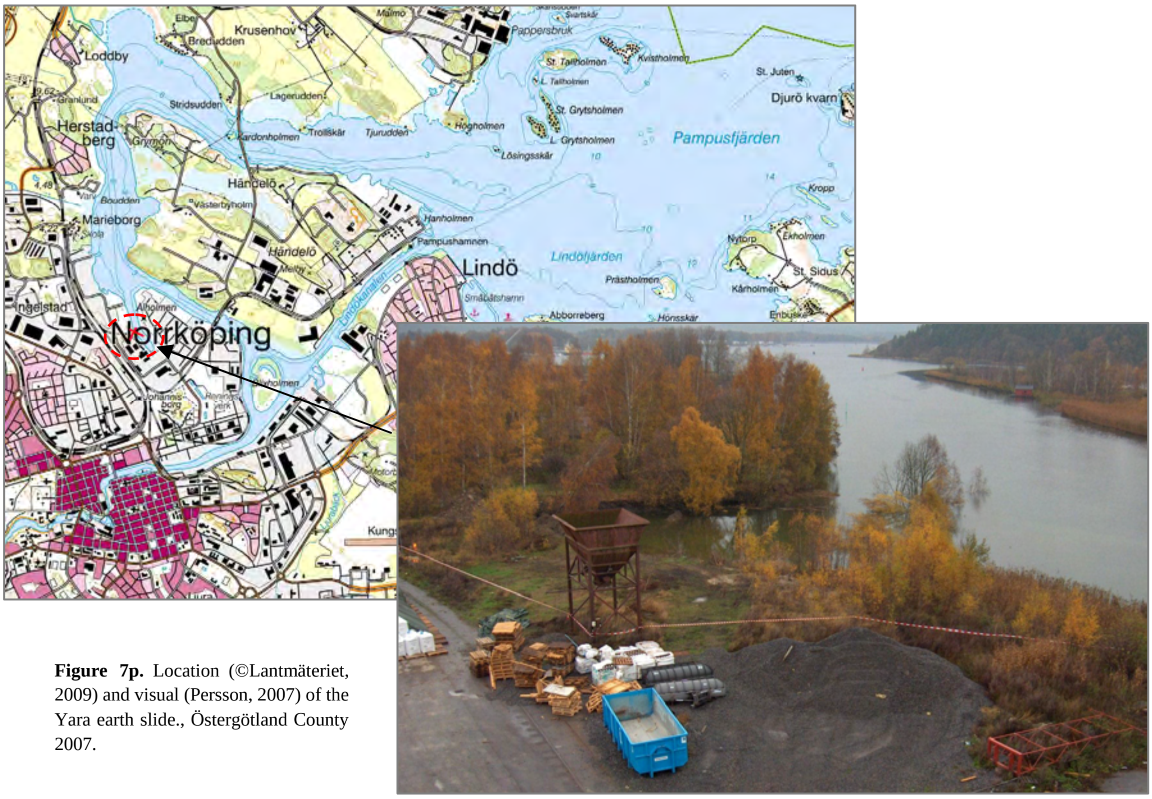


Figure 7p. Location (©Lantmäteriet, 2009) and visual (Persson, 2007) of the Yara earth slide., Östergötland County 2007.

7.2.5. Götaskredet, Västra Götaland

The 1957 Göta earth slide, involving the displacement of an area of about 370 000 m^2, is one of the largest and most destructive mass movements on record in Sweden (SGI, 2009). Preceded by the gradual development and widening of a bow-shaped crack that same morning, the main movement took place during midday on the 7th of June, within a pulp-mill industrial site located approximately 50 kilometres upstream the river's debouchment into the sea by the city Göteborg (fig. 7q). Ensuing geotechnical studies classified the slide as retrogressive and rotational, occurring within thick, 20-50 m deep deposits of clay and along a thin but distinct interbedding of silt and sand (Odenstad, 1958). Intensified riverbank erosion due to increases in traffic along the river, artesian groundwater and patches of quick-clay detected within the more landward parts of the slide area was subsequently considered jointly causative for the occurrence and the ultimate extent of the event. Also, there were discussions on whether process waste in the form of sulphur lye – which was detected through local groundwater-analyses – could potentially have caused a reduction in the shear strength of the clay through chemical alterations of the same (Odenstad, 1958).

Before the slide, the affected reach was characterised by its relatively steep river banks, in places reaching heights of 7-8 metres, making a sharp contrast to the otherwise flat surroundings. During the slide, this situation changed abruptly. An approximately 1.5 km long and 250 m wide stretch of the bank was then increasingly displaced as the movement gradually progressed in an upstream, i.e. northward- and inland-direction (Odenstad, 1958). Ultimately the ground within the subaerially affected reaches had subsided with as much as 8 metres with the slide-masses having been transported up to 70 metres into the previously 120 m wide river, causing extensive, although not complete, damming (Wide, 1972; fig. 7r). Large portions of the yard and the buildings of the factory were hence completely destroyed. Material damage was extensive, three men died, several more were injured and large amounts of plausibly contaminated scree lay uncovered and exposed to both wind and water (fig. 7s). This necessitated rapid stabilisation measures in order to prevent further damage. Also, extensive dredging had to be undertaken and eventually more than 1 000 000 m^3 of material was removed (Wide, 1972; Odenstad, 1958).

During the slide, a major surge causing extensive damage along both shorelines was noted by several witnesses along the upstream parts of the river (Melander, 1997; Odenstad, 1958). Forming in response to the initial movement, it was seen to progress together and seemingly alongside with the slide. It was later discussed whether the slide and the wave were acting so as to mutually enforce one and another. The slide through gradually compressing the river section thereby adding energy to the wave movement, and the wave through lowering the water table thus river-bank support and strength upon passage of the wave trough. By the northernmost parts of the slide area, the wave height was estimated at 5-8 metres. 2.5 kilometres further upstream, it was approximated at ~3.5 metres height (Odenstad, 1958). No wave was detected downstream.

Figure 7r. Spatial distribution, noted features and effects of Götaskredet, Västra Götaland County 1957. Adopted from Odenstad (1958).

Figure 7s. Photograph showing the major damage caused by Götaskredet. The remains of the factory can be seen in the middle of the picture. From Odenstad (1958).

Figure 7q. Location of the Göta earth slide (topmost circle) and the Agnesberg earth slide (lowermost). Basemap from ©Lantmäteriet (2009).

7.2.6. Agnesberg, Västra Götaland

The Agnesberg landslide occurred on the 14th of April 1993. It occurred within an industrial site located along and upon the eastern bank of the Göta Älv river, some 10 kilometres upstream central Göteborg and about 2.5 kilometres upstream the regional fresh-water intake Alelyckan (fig. 7q). The land area affected ultimately reached some 9 600 m^2, with an approximately 80 m long and 50 m wide stretch of the river bank having slided into the river through a retrogressive, rotational movement (SGI, 2009). A 100 m long and 80 m wide stretch of the river was hence dammed as it was covered in ~2 metres of sensitive clay (Larsson et al., 1994).

The site of failure was located within and along a stretch of the river characterised by thick (35 m deep) deposits of sensitive clay resting upon likewise thick deposits of sand with interbedded silt and clay layers (Larsson et al., 1994). Quick-clay was known to be present and geotechnical studies later detected substantial artesian groundwater pressures within the sand layers. Towards the north the slide area was limited by a distinct change in the soil stratum in the form of 4 m thick deposits of sand and silt deposited in and around a passing creek. Topographically, the area can best be described as somewhat superficially flat with a steep subaqueous slope, just at the angle of repose, located some 24 metres into the channel bed, making a sharp contrast to the otherwise plane surroundings (Larsson et al., 1994) (fig. 7t).

Since no real-time observations were made, the course of the slide was subsequently analysed based largely on recordings of turbidity made continuously at the Alelyckan intake. These also served to demonstrate the carrying capacity of a slide of this magnitude. At the day of the slide, three major sediment pulses were registered, hence indicating three successive movements (fig. 7u). The first pulse was timed at approximately 6 am whereby the level of turbidity increased from 4 to 10 FTU. The second pulse occurred roughly three hours later, demonstrating an even greater increase in turbidity going from 4 to 12 FTU. The third and last pulse was dated at about 12.30 pm - 6 hours after the initial event - whereby the level of turbidity increased from 7 to 9 FTU (Larsson et al., 1994).

Of the three events, only the two latter were actually witnessed live. Based on ensuing studies, it was concluded that the movement ought to have started as a subaqueous slide along the subaquatic slope, in turn triggering and successively causing the main and the third and last movement some three and six hours later, respectively (Larsson et al., 1994). Passing ships were also believed to have influenced the course of the events, potentially imposing transitory stresses along the already sensitive reach.

Dredging was later undertaken in order to restore the channel morphology. However, due to major concerns of further movement/-s, stabilisation measures were first completed both on land and along the channel bed (Larsson et al., 1994).

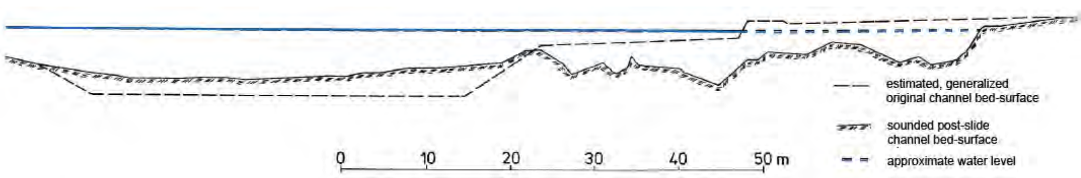


Figure 7t. Estimated pre-slide- and sounded post-slide-transect of the affected reach of the river. Adopted from Larsson et al. (1994).

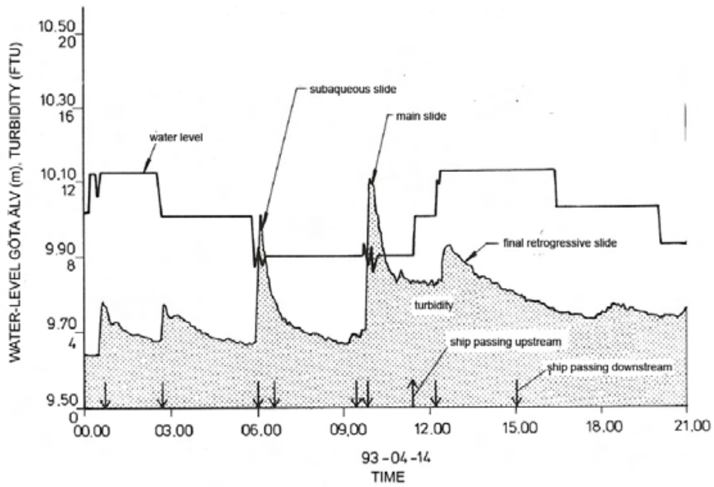


Figure 7u. Measurements of water level and turbidity at Alelyckan 2.5km downstream the site of failure at the day of the slide. Adopted from Larsson et al. (1994).

Name (yr)	Type	Material	Size	Geography/Geology	Key observations
Tångböle (1995)	earth slide/fall	clay, silt	~200 000m³	30-40m high, steep, clayey-silty, forested river bank in sparsely populated region	- widespread and long-term increases in levels of turbidity and rates of downstream sedimentation - local hydrogeological disturbances including signs of pollution
Öd 1 (2002)	translational earth slide/fall	silt/fine sand	~31 000m³	40-45m high, steep, silty, cultivated river bank in sparsely populated region	- influence(-s) of ice on river upon time of movement - major forces involved at time of movement - long-term (permanent) damming and associated alterations of flow- and erosion patterns
Trossnäs (1969)	rotational earth slide	clay (sand, silt)	~100 000m³	clayey, forested, relatively flat stretch of river in a relatively developed and densely populated region	- extensive up- and downstream damming - rates of erosion and sediment transport - downstream alterations in color, temperature, visibilty
Yara (2007)	earth slide	fills, clay	~1 200m²	industrial site within clayey harbor -area in densely populated region	- damming - permanent shore-line displacement - short- and long-term release of contaminants from displaced masses - importance of type of contaminant
Götaskredet (1957)	rotational earth slide	clay	~370 000m²	industrial site along relatively steep, clayey river bank within densely populated area	- evolution of movement - extensive onshore soil subsidence and offshore damming - up- and downstream surging
Agnesberg (1993)	rotational earth slide	clay	~9 600m²	industrial site along seemingly flat, clayey river bank within densely populated area	- importance of subaquatic topography - evolution of movement - sediment transport capacity and processes

Table 7v. A summary of the key characteristics of-, and the key observations made in connection to, the six mass movement events reviewed in the text. Note the varied units in the size-column.

8. Discussion

8.1. Concept validation

Reviewed mass movement events have served to validate the hazard conceptualisation originally put forward by Göransson et al. (2009). Little documentation exists of actual associated contaminant release and transport. However, hypothesised mobilisation mechanisms appear to develop according to the theorised system description. The disturbance and exposure of soils, sediments and groundwater within the initiate zone to the air and the water of the SWS is observed in connection to most events. The same is true for the stirring of soils and sediments within the run-out zone, and, the initial surging. The far-field transport of materials set into suspension into the 2nd run-out zone is not as commonly documented, however, it has been noted and the lack of documentation is more likely to result from a lack of recognition given long-term effects rather than a true lack of occurrence of transport. The following findings are worth underlining:

- Damming is almost always associated with slope failure in connection to a water body. If the entire SWS is blocked, then considerable upstream areas may be inundated and subject of contaminant mobilisation. Upon dam-break and the formation of a dam-break wave, mobilised materials will be likely to travel for long distances over relatively short amounts of time. This adds substantial areas to bear in mind upon risk assessment.
- If the damming is partial, effects on channel bed morphology and sedimentary composition can still be of such a spatial and temporal extent so that significant alterations of circulation patterns, flow rates, carrying capacities and erosive traits of the SWS might persist for years (or more or less permanently). The narrowing of the channel will favour an increase in transport and erosion according to fundamental physical laws. The possibility of an increased flow rate and subsequent effects in terms of enhanced transport and erosion is hence also an important aspect to bear in mind.
- The effects of impulse-generated waves are not only constrained to downstream reaches. Surges may travel for several kilometres also *against* ruling circulation patterns, potentially mobilising sediments and contaminants along upstream reaches, and, potentially also inducing further failure as hypothesised in the Göta example. It is also important to recognise the fact that surges may grow as they move throughout the system, and, that their reflections may be likewise damaging.
- Materials set into suspension upon the main movement may stay in suspension for months and affect surface water as well as groundwater quality several tens to hundred of kilometres downstream. Furthermore, displaced masses, which may reach volumes of millions of cubic metres, may be subject of enhanced erosion over years to come, inferring increased amounts of suspended material and associated environmental effects within the affected SWS for just as long.

Concerning factors likely to be decisive for the extent and character of the hazard as hypothesised in chapter 4, some conclusions can be drawn based on made observations. One is the importance of the *morphology of surrounding reaches*. This is a factor that has proved imperative both in terms of initial hazard potential (scope and state of main movement), and in terms of further far-field transport, deposition and material mobilisation for most of the reviewed events. The same is true for the *sedimentary composition of surrounding reaches* which together with *ruling hydrodynamic properties* are clearly the two most important factors in terms of spatial and temporal extent of mobilisation and spread of materials; both in a short- and a long-term perspective. For Swedish concerns specifically, it is worth emphasising that silts and clays - being the two most common materials involved in mass movements here - are the two lightest thus most easily transportable sedimentary fractions. They also represent those types of materials that particle-bound contaminants most commonly tend to be associated with (Larson et al., 2007). Thus, the Swedish mass movement hazard is of such a character that it tends to favour far-field particle-bound contaminant transport.

The potential influence of *type of movement* of the hazard potential also ought to be recognised in this context. It is likely to believe that a flow would infer a greater mobilisation potential because of its inherited viscous properties. It might also be hypothesised that rotational earth slides, because of their relatively lower grade of internal deformation, would be less easily mobilised than e.g. translational slides/falls. However, reviewed documentation does not provide sufficient support for these theories. More relevant observations of different types of movements would be needed.

The influence of the chemical, biological and physical properties of surrounding reaches and media on the hazard extent and character has not been able to analyse in much detail in this study since virtually no documentation of such influences exist for relevant events. They are, however, bound to exist and the predisposed enrichment of cadmium and zinc within the water body in connection to the Yara earth slide at least serve to demonstrate the importance of the *type of contaminant/-s* involved.

8.2. Hazard extent

As mentioned earlier, the studied reaches along Viskan, Klarälven and Ångermanälven only make up for a very small proportion of the total length of Swedish shorelines susceptible of mass failure. Furthermore, only areas at direct risk from slope failure were considered in the study. No concern was given opposite river banks, up- or downstream areas potentially affected by the movement.

The studied reaches are not extraordinary in terms of historical/contemporary industrial activities and sites of established/potential soil contamination, at least not for exploited regions throughout the country. They were chosen based on amount of relevant information readily available, and, because of the variation in geographic locations and geological settings, *not* with any preconceptions on the amount of risk objects that potentially would be found. It is interesting to note, therefore, the extent to which they are all subject of the assessed hazard. Hence, if these areas are to be considered representative for national conditions, then most of the major river systems as well as considerable parts of lake shorelines and coastal areas throughout the country are to be considered at risk of contaminant transport in connection to mass failure. Especially when considering the commonly prolonged temporal and spatial effects of a movement as discussed above.

Two major lessons are to be learnt from conducted hazard investigations.

- The nature and scope of the hazard and associated risks varies with *geographical location* in accordance with inherited geologic, climatic and biologic conditions, and, with site-specific extent and character of human influence. The latter refers both to potential anthropological influence in terms of mass movement probability, and, in terms of type and extent of pollutant activities.
- Seasonal changes will alter the hazard potential both in terms of modifications of hydrodynamic properties of the SWS, and in terms of modifications of chemical, biological and physical (incl. hydrogeological) properties of surrounding media. The scope and nature of the hazard and associated risks thus also varies with *time*.

Conclusively, it is hard to make any further generalisations on the scope of the mass movement-contaminant release and transport hazard other than that it is in deed of national extent, and, that its nature varies somewhat predictably in accordance with time and location according to the above. Each potential risk area needs to be assessed individually in order to thoroughly and accurately evaluate hazard character and potential, what mitigation measures might be needed and how these can best be optimised. Here, the importance of measures of vulnerability and site-specific environmental and societal values ought to be stressed since these will also influence the need for, or rather the perception of need for, risk management.

Furthermore, in this context, potential effects of climate change must be stressed. If predictions of increases in temperatures, precipitation, run-off and mass movement occurrence come true, then the extent of the studied hazard will increase, and, its character is likely to be modified according to imposed environmental changes. This infers another aspect to bear in mind upon evaluating the need for risk assessment and also upon developing appropriate assessment techniques.

8.3. Hazard recognition, risk perception and responsibility matters

The assessment of the national extent and character of the mass movement contaminant-release and transport hazard can be considered the main aim of this study. As this assessment has been undertaken, another just as or even more important aspect of the problem has been highlighted, namely that of the lack of recognition given the hazard, and the inherited lack of perception of associated risks. The restricted amount of documentation regarding environmental and long-term/far-field effects of historical events is one factor indicative of this. The fact that slope failure generally does not appear to be considered as part of potential spreading conditions upon environmental risk assessment of sites of established/suspected soil contamination is another, and the fact that environmentally hazardous facilities are built and granted a permit of operation within areas susceptible of slope failure is yet another. Through systematic questioning of concerned authorities, it becomes evident that the lack of recognition is not what might first seem as a matter of neglect but in deed one of failure to recognise the hazard at all. In effect, upon confrontation, few seem to have given the matter any consideration whatsoever. Most instead appear to have some sort of revelation wherein their perception of risks associated with slope failure hazards goes from being restricted to those associated with damages to the *built* environment, to those potentially affecting the *natural* environment. Hazard and risk awareness raising might accordingly represent the most important and most effective task to undertake in terms of future mitigation measures.

Another critical concern is to do with a confusion of where and with whom associated responsibilities lie. Governmental authorities and sources of funding and expertise are separate in terms of the geotechnical aspect of the mass movement hazard on the one hand, and pollution-related hazards on the other. The problem recurs throughout all levels of society and is exemplified by the amount of people/divisions that have needed to be questioned at any given local authority in order to recollect relevant experiences and risks: one from the emergency management/civil protection unit, one from the community development unit and at least one from the environmental unit. Within the environmental unit in turn, there is furthermore typically a division made between concerns relating to (i) the assessment/remediation of contaminated soil, (ii), the licensing/monitoring of environmentally hazardous facilities, and (iii), general environmental monitoring. The complexity is obvious and so for the future, clarification of responsibilities, as well as incorporation of the mass movement–contaminant release and transport hazard into relevant laws and mitigation measures, will be needed.

8.4. Limitations of study and recommendations for future studies

This study has focused only on Swedish conditions, experiences and risks. The hazard is, however, bound to be largely global. It would be interesting to see therefore, what lessons could be learnt from abroad. Even though lack of attention, documentation and research based on initial screenings appear as global, inventories of the kind presented here would undoubtedly prove valuable. They would also, hopefully, serve to raise awareness of a hazard that might prove even more troublesome in the future, depending on effects of climate change.

The application of Geographic Information Systems in order to identify and evaluate risk areas can also be greatly improved for the future. Factors such as slope inclination and soil-, contaminant- and SWS-properties, mass movement probabilities, environmental and societal vulnerabilities of *all* (up/downstream) reaches at risk from the initial movement as well as seasonal variations could be programmed so as to be accounted for and thus incorporated into the assessment. The development of a targeted GIS-application would substantially facilitate and make further site-specific hazard and risk analyses, as well as subsequent mitigation measures, more effective.

A last important point to make is that much of the knowledge needed in order to be able to further elaborate on the mechanics of the mass movement-contaminant release and transport hazard potentially might already exist, albeit within different scientific disciplines and contexts. Hence, if the need for a targeted knowledge basis was clarified, and if proper incentives of interdisciplinary research were given, much scientific progress, as well as much progress in terms of development and implementation of proper risk mitigation measures, would probably be possible in the not too distant future.

9. Conclusions

- Mass movements occur repeatedly in Sweden and are mainly concentrated to river basins located well below the highest shoreline, in connection to areas along the north of the west- and the north of the east coast. Of roughly 400 studied events, 95% have occurred into or in close connection to surface water systems. 90% of these have primarily affected running waters, 5% lakes and 5% open waters. The most affected SWS are in descending order: Göta Älv, Ångermanälven, Piteälven, Luleälven, Klarälven, Viskan, Moälven, Dalälven and Umeälven.
- Earth slides represent the most common type of movement with rotational events in clays being typical of the SWS located within the more southern and interior parts of the country. Earth and debris flows are also known from these regions. Further north, translational earth slides and falls in siltier deposits dominate along SWS there, with earth and debris falls and flows subordinate. Volumes involved may in extreme cases be counted in millions of cubic metres.
- With the exception of isolated parts of north-western Sweden, environmentally hazardous facilities and established/suspected sites of soil contamination are widespread throughout the country. Areas along major river systems, lakes and coastal harbors are those areas most affected since this is where most industries historically have been and continue to be localised.
- Within the three studied risk areas along Viskan, Klarälven and Ångermanälven, 102 environmentally hazardous facilities/sites of established or suspected soil contamination were identified. Of the 44 sites of potential or established soil contamination at direct risk of failure, only one has been classified as a “very high risk”-object according to national environmental risk assessment criteria. The nature and scope of the hazard and associated risks varied between and within the studied areas.

A certain geographical zonation of contemporary and/or historical pollutant activities, indicative of type of potential contaminants present, was also noted between them. Wastewater treatment plants, municipal or industrial landfills and petrol stations were present within all areas.

- Upon the occurrence of a mass movement into a SWS, displaced materials (including potential contaminants) may:
  - cause damming and further mobilisation of sediments/contaminants through
    - upstream inundation
    - downstream erosion due to the eventual formation of a dam-break wave
    - alterations to downstream flow- and erosion patterns that may last for years or be permanent
  - be carried up- and downstream for several kilometres through initial, impulse-generated waves that in turn may mobilise further sediments/ contaminants through erosion of hit reaches
  - stay in suspension for several months, being carried downstream for distances of several tens to hundred of kilometres, affecting the quality and character of the SWS and surrounding media.
- Ultimate effects in terms of associated contaminant release and transport will vary with time and location according to concurrent geologic, climatic and biologic conditions. Environmental and societal values will determine the perception, assessment and management of risks.
- The full scope of the Swedish mass movement hazard and associated environmental risks has so far not been fully recognised. There is a need for
  - incorporation of the mass movement-contaminant release and transport hazard into relevant laws and mitigation measures,
  - clarification of responsibilities,
  - more interdisciplinary collaboration, research and exchange of experiences, both nationally and internationally.

10. Acknowledgements

First and foremost, I thank Gunnel Göransson at the Swedish Geotechnical Institute for presenting me with such an interesting task. I am very grateful that I have been able to spend all the time and effort a work of this sort requires into a subject which I find really, truly interesting. I also thank you for all your support and constructive criticism throughout these months. I also thank Prof. Per Möller, my supervisor at the Department of Geology in Lund, for your support and especially all the read-throughs you have taken on.

I would also like to thank Jan Fallsvik, Ann-Christine Hågeryd, Ingrid Gårlin, Anders Salomonson and Eva Albin at SGI for your respective assistance throughout various stages of my research. David Bendz and the entire Malmö office also needs to be acknowledged since without you, I would not have enjoyed these months as much as I have. I am thankful for you lending me a desk, helping me out and making me feel like home so quickly. I will miss you all.

All of the people I have been in contact with throughout this study who have shown a true interest in my work and who have made an effort to help me out – I am deeply grateful to you all. I hope you find the report interesting and of value to your respective fields of interests.

Last but not least, family and friends, thank you for putting things in their right perspective.

11. References

Alén, C., Bengtsson, P.-E., Berggren, B., Johansson, L. & Johansson, Å., 2000. *Skredriskanalys i Göta älvdalen - Metodbeskrivning* (SGI Rapport Nr 58). Linköping: Swedish Geotechnical Institute. 106 pp.

Andersson-Sköld, Y., Nyberg, H. & Nilsson, G., 2007. *Föroreningsspridning vid översvämningar - Etapp I* (SGI Varia Nr 576). Linköping: Swedish Geotechnical Intitute. 40 pp.

Andersson, M., 2009. Sverige - Näringsliv - Miljösituation. In *Nationalencyklopedin*. Available from: http://www.ne.se [Accessed 9th September 2009].

Axelsson, K., Bengtsson, P.-E., Engström, P., Fredriksson, A., Larsson, R., Nyberg, M., Ottosson, E., Rankka, K., Schälin, J., Sellgren, E., Sällfors, G. & Zackrisson, P., 1995. *Anvisningar för släntstabilitetsutredningar* (Skredkommissionen Rapport 3:95). Linköping: IVA Commission on Slope Stability/Swedish Geotechnical Institute. 208 pp.

Bell, F.G., 1999. *Geological hazards: their assessment, avoidance and mitigation*. New York: Routledge. 648 pp.

Bergström, S. 1999. *Höga vattenflöden i reglerade älvar* (Fakta Nr 1). Norrköping: Swedish Meteorological and Hydrological Institute. 10 pp.

Centre for Research on the Epidemiology of Disasters [CRED], 2008. *EM-DAT: Emergency Events Database*. Available from http://www.emdat.be [Accessed 6th May 2009].

County Administrative Board of Värmland [VL], 1969. *Sammanträde med anledning av raskatastrof i Norsälven norr Nors - kyrka.* Unpublished promemoria and meeting protocols (12th-22nd April 1969). Vålberg: County Administrative Board of Värmland.

County Administrative Board of Värmland [VL], 2009a. *GIS-underlag* (översiktliga skredkarteringar 87-98, 04-06 // miljöfarligverksamhet A+B-anläggningar // förorenad mark *as .shp-files*). E-mail to: maria.akesson@swedgeo.se from Håkan Kjörsträd, GIS-unit [Received 18th September 2009].

County Administrative Board of Värmland [VL], 2009b. *Utdrag ur MIFO-databasen* (as .doc-files). E-mail to: maria.akesson@swedgeo.se from Björn H. Nilsson, Environmental Protection Unit [Received 30th October 2009].

County Administrative Board of Västernorrland, 2009a. *Potentiellt förorenade områden* (geographic information as *.shp-file*, data on specific objects as *.doc-file*). E-mails to maria.akesson@swedgeo.se from Annika Dahl, Environmental Administrator [Received 2nd October and 16th November 2009].

County Administrative Board of Västernorrland, 2009b. *Utdrag ur EMIR* (*as .xls-file*). E-mail to maria.akesson@swedgeo.se from Annika Dahl, Environmental Administrator [Received 26th October 2009].

County Administrative Board of Västra Götaland, 2002. *Miljögifter i avloppsslam* (Report Nr 2002:39). Göteborg: County Administrative Board of Västra Götaland. 91 pp.

County Administrative Board of Västra Götaland, 2009a. *MIFO-objekt i Mark, Borås, Ulricehamn och Svenlunga* (*as .xls file)*. E-mail to: maria.akesson@swedgeo.se from Uffe Schultz, Environmental Protection Unit [Received 30th October 2009].

County Administrative Board of Västra Götaland, 2009b. *Tillståndspliktiga anläggningar i kommuner i Viskans avrinningsområde* (*as .xls file)*. E-mail to: maria.akesson@swedgeo.se - from Sten Wolme, Environmental Protection Unit [Received

10th November 2009].
Cruden, D.M. & Varnes, D.J., 1996. Landslide Types and Processes. In: A.K. Turner and R.L. Schuster (eds.) *Landslides: investigation and mitigation* (Transportation Research Board Special Report 247). Washington D.C.: :National Academy Press. pp. 36-71.
Dilley, M., Chen, R.S., Deichmann, U., Lerner-Lam, A.L., Arnold, M., Agwe, J., Buys, P., Kjekstad, O., Lyon, B. & Yetman, G., 2005. *Natural Disaster Hotspots: A Global Risk Analysis* (Disaster Risk Management Series No. 5). Washington D.C.: The World Bank. 148 pp.
Ehlin, U. & Zachrisson, G., 1969. *Spridningen i Vänerns nord västra del av suspenderat material från skredet i Norsälven i April 1969* (Serie Hydrologi Vol 7). Stockholm: Swedish Meteorological and Hydrological Institute. 15 pp.
Ekberg, L., Åkesson, O., Harrami, O. & Rundström, H., 1995. *Utvärdering av den kommunala räddningstjänsten i samband med översvämningarna våren 1995* (Observatörsrapport). Karlstad: Statens Räddningsverk. 48 pp.
Fallsvik, J., Hågeryd, A.-C., Lind, B., Alexandersson, H., Edsgård, S., Löfling, P., Nordlander, H. & Thunholm, B., 2007. *Impact of the climate change in Sweden. Overview of assessment of soil movements due to climate change* (SGI Varia Nr 571). Linköping: Swedish Geotechnical Institute. 34 pp.
Fredén, C., 1996. Erosionsrisker längs älvarna i Sollefteå Kommun. *SGU Rapporter och Meddelanden: Miljögeologi 85*, 23-28.
Fredén, C., 2002. *Släntskredet vid Öd, Sollefteå Kommun* (SGU-rapport 2002:32). Uppsala: Geological Survey of Sweden.
Fredriksson, M., 1995. *Övre_2.jpg*. E-mail to: maria.akesson@swedgeo.se [Received 14th May 2009].
Geological Survey of Sweden [SGU], 2000. *Map of the Quaternary Deposits 10D Karlstad NV* (Ser Ae 140). Uppsala: Geological Survey of Sweden.
Geological Survey of Sweden [SGU], 2009. *Landslides and gullies*. [Online] Available from http://www.sgu.se [Accessed 27th November 2009].
GeoNet, 2009. *GNS Science: Landslide Glossary*. [Online] Available from: http://www.geonet.org.nz/landslide/glossary.html [Accessed 27th November 2009].
Gullersbo, Å. Engineer, Community Development Unit, Sollefteå Municipality. (Personal communication 13th August 2009).
Göransson, G.I., Bendz, D. & Larson, P.M., 2009. Combining landslide and contaminant risk: a preliminary assessment. A study of the Göta Älv river Valley, Sweden. *Journal of Soils and Sediments 9*, 33-45.
Hultén, C., Olsson, M., Rankka, K., Svahn, V., Odén, K. & Engdahl, M., 2005. *Släntstabilitet i jord. Underlag för handlingsplan för att förutse och förebygga naturolyckor i Sverige vid förändrat klimat. Deluppdrag I* (SGI Varia 560:1). Linköping: Swedish Geotechnical Institute. 50 pp.
IAEG Commission on Landslides [IAEG], 1990. Suggested nomenclature for landslides. *Bullentin of the International Association of Engineering Geology 41*, 13-16.
Jerbo, A. & Sandegren, E., 1963. *Skredet i Kyrkviken vid Kramfors, 1-4 februari 1959: The landslide at Kramfors on the Kyrkviken* (Meddelande från Kungliga Järnvägsstyrelsens Geotekniska Avdelning Nr 7). Stockholm: Kungliga Järnvägsstyrelsen. 28 pp.
Karlsson, M.. Product Flow Manager, Yara AB. (Personal communication 14th May and 1st June 2009).
Karlstad Kommun, 2009. *Karlstad Kommun - Vatten.* [Online] Available from: http://www.karlstad.se [Accessed 2nd October 2009].
Kjekstad, O. & Highland, L., 2009. Economic and Social Impacts of Landslides. In: K. Sassa and P. Canuti (eds.) *Landslides - Disaster Risk Reduction*. Berlin, Heidelberg: Springer-Verlag Berlin Heidelberg. pp. 573-587.
Kristensson, M., 2000. *Översiktlig stabilitetskartering i Marks Kommun*. Unpublished report. GF Konsult AB. 13pp.
Lantmäteriet, 2009. *Digitala Kartbiblioteket.* Gävle 2009: I2008/1951.
Larsen, O., Davison, W., Vamvakopoulos, K. & Möhlenberg, F., 2007. Fine Sediment Particles. In: B. Westrich and U. Förstner (eds.) *Sediment Dynamics and Pollutant Mobility in Rivers - An Interdisciplinary Approach*. Environmental Science and Engineering. Berlin, Heidelberg: Springer-Verlag Berlin Heidelberg. pp. 305-342.
Larson, M., Bendz, D., Nilsson, G. & Hultén, C., 2007. *Slope failure in contaminated areas - spreading of pollutants to surface waters in a changing climate.* Unpublished grant application (FORMAS). 32 pp.
Larsson, R., Ottosson, E. & Sällfors, G., 1994. *Agnesbergsskredet* (SGI Rapport Nr 44). Linköping: Swedish Geotechnical Institute. 73pp.
Lindskog, G. & Wager, O., 1970. *Skredet i Norsälven vid Trossnäs, Värmlands Län, 12 april 1969.* Stockholm: Swedish Geotechnical Institute. 18 pp.
Lundgren, F., Forsberg, J. & Göransson, M., 2008. *YARA, Ståthögaviken, Norrköping. Miljöteknisk sedimentundersökning och ytvattenprovtagning*. Unpublished report. Malmö: WSP Environmental. 10 pp.
Marks Kommun, 2008. *Viskan tillgänglig för alla.* Mark: Marks Kommun. 10 pp.
Mark Municipality, 2009. *GIS-underlag* (översiktlig stabilitetskartering *as .ai-files* and local geodatabase for referencing). Provided for by Patrik Malvenius, GIS-unit.
Meehan, W.R., 1991. *Influences of Forest and Rangeland Management on Salmonid Fishes and Their Habitats* (American Fisheries Society Special Publication No 19). Bethesda, Maryland: U.S. Department of Agriculture, Forest Service. 622pp.
Melander, T. (ed.), 1997. *Göteborgs Geotekniska Historia - några sonderingar*. Göteborg: SGF Väst. 128 pp.
Nationalencyklopedin [NE], 2009a. *Klarälven*. [Online] Available from http://www.ne.se [Accessed 2nd October 2009].
Nationalencyklopedin [NE], 2009b. *Ångermanälven.* [Online] Available from http:// www.ne.se[Accessed 2nd October 2009].
Nilsson, P., 2005. *En sedimentundersökning i Åresjön*. Unpublished report. Åre: County Administrative Board of Jämtland. 10 pp.
Odenstad, S., 1958. Jordskredet i Göta den 7e juni 1957. *GFF 492 (80)*, 76-86.
Olofsson, H., 2009. *Samordnad recipientkontroll i Viskan 2008.* Halmstad: ALcontrol AB//Viskans Vattenråd. 94 pp.
Persson, R., 2007. *PM angående skred vid Ståhögaviken*. Unpublished promemoria. Landskrona: Yara AB.
Persson, R., 2008. *PM angående jordskred inom fastigheten Slottshagen - Statusbeskrivning i februari 2008 och förslag till fortsatt handläggning*. Unpublished promemoria. Landskrona: Yara AB.
Picarelli, L., Oboni, F., Evans, S.G., Mostyn, G. & Fell, R., 2005. Hazard characterization and quantification. In: O. Hungr, R. Fell, R. Couture and E. Eberhardt (eds.) *Landslide Risk Man agement*. London: A.A. Balkema Publishers. pp. 27-61.
Schuster, R.L. & Highland, L.M., 2007. Overview of the Effects of Mass Wasting on the Natural Environment. *Environmental & Engineering Geoscience 13:1, 25-44.*
Selby, M.J., 1993. *Hillslope materials and processes.* Oxford: Oxford University Press. 451 pp.
Sjöberg, V., 1969. *Norsälvens vatten och stränder*. Unpublished report. Vålberg.
Smith, K., 2001. *Environmental hazards: assessing risk and reducing disaster.* London: Routledge. 392 pp.
Sundborg, Å., 1973. *Indalsälven, Ljungan, Ljusnan, Dalälven, Klarälven: Geovetenskapliga naturvärden. Evaluation of five Swedish rivers* (UNGI Rapport 27). Uppsala: Naturgeografiska Institutionen, Uppsala Universitet. 137 pp.
Svenskt Vatten, 2009. *Varifrån kommer dricksvattnet?* [Online] Available from http://svensktvatten.se [Accessed 22nd January 2010].
Svensson, T., Persson, H. & Midboe, F., 2006. *Effekter i Ångermanälven från skred i nipor nedströms Sollefteå: dokumentation och beräkningar*. Karlstad: Nätverket för älvsäkerhet, Karlstads universitet. 54 pp.
Sweden's County Administrative Boards and Water Authorities, 2009. *Vattenkartan.* [Online] Available from http:// www.gis.lst.se/vattenkartan/ [Accessed 5th May 2009].
Swedish Civil Contingencies Agency [MSB], 2007. *Översiktlig stabilitetskartering Västernorrlands Län* (as .shp-files). Provided for by SGI with permission of Susanne Edsgård, MSB.
Swedish Environmental Protection Agency [SEPA], 1999. *Metodik för inventering av förorenade områden* (Rapport 4918). Stock-

holm: Swedish Environmental Protection Agency. 152 pp.
Swedish Environmental Protection Agency [SEPA], 2008a. *Internationella krav på utsläppsrapportering*. [Online] Available from http://www.naturvardsverket.se/ [Accessed 27th November 2009].
Swedish Environmental Protection Agency [SEPA], 2008b. *Tillstånd och anmälan för miljöfarlig verksamhet.* [Online] Available from http://www.naturvardsverket.se/ [Accessed 27th November 2009].
Swedish Environmental Protection Agency [SEPA], 2009a. *Lägesbeskrivning av efterbehandlingsarbetet i landet 2008.* Governmental Report. Stockholm: Swedish Environmental Protection Agency. 12 pp.
Swedish Environmental Protection Agency [SEPA], 2009b. *Sweden's Environmental Obectives in Brief*. Stockholm: Swedish Environmental Protection Agency. 34 pp.
Swedish Environmental Protection Agency [SEPA] 2009c. *Kemikalieutsläppsregistret*. [Online] Available from http://kur.naturvardsverket.se:7001/kur/ [Accessed 2nd November 2009).
Swedish Geotechnical Institute [SGI], 2009. *Skreddatabas.* Unofficial database. Linköping: Swedish Geotechnical Institute.
Swedish Meteorological and Hydrological Institute [SMHI], 2005. *Klimatscenarier från 2005.* [Online] Available from http://www.smhi.se/sgn0106/if/rc/clmscen05.htm [Accessed 14th December 2009].
United Nations International Strategy for Disaster Reduction [UNISDR], 2009. *Terminology: Basic Terms of Disaster Risk Reduction.* [Online] Available from http://www.unisdr.org/eng/library/lib-terminology-eng%20home.htm [Accessed 15th December 2009]
Varnes, D.J., 1978. Slope movement types and processes. In: R.L.. Schuster and R.J. Krizek (eds.) *Landslides Analysis and Control*. Transportation Research Board Special Report 176. Washington D.C.: National Academy of Sciences.
Viberg, L., Fallsvik, J. & Hågeryd, A.-C., 1989. *Inventering av stabilitetsförhållandena utmed delar av Ångermanälven och kusten i Kramfors Kommun*. Unpublished report. Linköping: Swedish Geotechnical Institute.
Viberg, L., Hågeryd, A.-C. & Jonsson, H., 2001. *Skreddatabas - ett förslag* (SGI Varia 512). Linköping: Swedish Geotechnical Institute.
Wastenson, L., Bernes, C. & Grundsten, C. (eds.), 1992. *National atlas of Sweden. The environment*. Stockholm: SNA Publishing.
Wastenson, L. & Fredén, C. (eds.), 2002. *National Atlas of Sweden. Geology*. Vällingby: SNA Publishing.
Wenner, C.-G., 1951. Data on Swedish Landslides. *GFF 73(2)*, 300-308.
Westrich, B. & Förstner, U. (eds.), 2007. *Sediment Dynamics and Pollutant Mobility in Rivers - An Interdisciplinary Approach*. Environmental Science and Engineering. Berlin, Heidelberg: Springer-Verlag Berlin Heidelberg. 430 pp.
Wide, Å., 1972. *Litteraturinventering av skred inträffade i Götaland till och med 1971.* Göteborg: Chalmers Tekniska Högskola, Göteborgs Universitet. 40 pp.

Appendix 1a

Risk objects along studied reaches of Viskan

Environmental hazardous facilities and sites of potential/established soil contamination within
(i) 150 meters distance of the river course, and,
(ii) stability zone 1 or 2 (in Mark Municipality).

	Name	Location x	Location y	Type of facility/activity responsible (status/detailed)	Stability zone (detailed)	MIFO-class
Environmentally hazardous facilities	Skene Avloppsreningsverk	6377340	1309400	wastewater treatment plant	1 (clay/si/sa on clay)	
Sites of established/potential soil contamination	Kinna Däckcentral/Texaco	6379680	1312440	petrol station // car care facility (closed; active 1960s-1989. Remediation measures undertaken)	1 (clay/si/sa on clay)	3
	OK-Västra	6378430	1312720	petrol station // car care facility (closed; active 1950-1985. Remediation measures undertaken)	1 (clay/si/sa on clay)	4
	Edvin Andersson mek verkstad	6379300	1312100	engineering industry (active)	1 (si/sa on clay)	-
	von Braun Properties AB	6377154	1310713	car care facility // sorting works (active)	1 (clay/si/sa on clay)	-
	Sahlins Maskin	6377245	1308898	engineering industry (active)	1 (clay/si/sa on clay)	-
	IGMAB	6365880	1302180	engineering/plastic industry (active engineering industry onsite; plastic industry 1998-2001)	2 (clay/si/sa on clay)	-
	Björketorps Handelsträdgård	6371169	1303152	nursery, market garden	1 (clay/si/sa on clay)	-
	Hulta Maskin Production AB	6375880	1308050	engineering industry (active)	1 (si/sa on clay)	-
	Assberg 1:36	6378350	1312285	engineering industry // car care facility (active since 1970s; some remediation measures undertaken)	2 (clay/si/sa on clay)	-
	Ånäs 7	6378900	1312600	multiple (closed varnishing-, active mechanical equipment rental-, oil installation- and piping industry)	2 (clay/si/sa on clay)	-
	Mezek Bil AB	6379078	1312459	car care facility // plate works (active)	2 (clay/si/sa on clay)	-
	Gamla Macken i Björketorp	6370910	1302760	car care facility // petrol station (active)	2 (clay/si/sa on clay)	-
	Markslöjd	6378200	1312360	textile industry (closed; active 1989-97)	2 (clay/si/sa on clay)	-
	CS Möbelfabrik	6363060	1299350	surface treatment of wood	2 (clay/si/sa on clay)	-
	Kinna Trävaru AB	6380208	1313114	timber trading industry (closed; active 1930-1999)	1 (si/sa on clay)	2
	Svenska Textilfilter	6378899	1312556	textile industry (active)	2 (clay/si/sa on clay)	-
	Skene Heden	6376555	1308565	waste landfill (closed; active 1934-1970)	1 (si/sa on clay)	3
	Brosäters Bed & Breakfast ARV	6365920	1302080	wastewater treatment plant (active)	1 (clay/si/sa on clay)	-
	Skene Avloppsreningsverk	6377340	1309400	wastewater treatment plant (active)	1 (clay/si/sa on clay)	-
	Horreds ARV	6362900	1299550	wastewater treatment plant (active)	1 (si/sa on clay)	-
	Björketorps ARV	6370500	1302950	wastewater treatment plant (active)	1 (clay/si/sa on clay)	-

Geographic information on stability zones from Mark Municipality (2009). Information on environmentally hazardous facilities/sites of potential/established soil contamination from the County Administrative Board of Västra Götaland (2009a, b).

Appendix 1b

Risk objects along studied reaches of Klarälven

Environmental hazardous facilities and sites of potential/established soil contamination within

(i) 350 meters distance of the river course, and,

(ii) stability zone 1 or 2.

	Name	Location x	Location y	Type of facility/activity responsible (status/detailed)	Stability zone (detailed)	MIFO-class
Environmentally hazardous facilities	Fordonsgasanläggning Sjövärnet	6587352	1371700	gaswork (under construction)	2	
	Avfallsvärmeverket Heden	6587200	1373000	waste treatment plant (located upon old landfill)	2	
	Bycosin / Bycotest AB	6586800	1371100	organic chemical engineering industry (active since 1940s)	1 (clay)	
	SITA Sverige AB	6585122	1371826	waste and residue treatment plant	2	
	Consale Product AB	6586470	1371870	composites/fiberglass industry	2	
	Centralsjukhusets Hetvattencentral	6586100	1367700	hot water central	2	
	Kosterns Hetvattencentral	6585700	1369100	hot water central	2	
	Sjöstadsverket	6587300	1371600	wastewater treatment plant	2	
	Skåre Avloppsreningsverk	6593410	1366100	wastewater treatment plant (5 650ppl connected)	1	
Sites of established/potential soil contamination	Öjenäs	6601330	1365960	metallurgy	2	4
	Kanikenässågen	6585720	1369746	sawmill / tier (closed; active 1905-67. Remediation measures ongoing)	1 (clay)	3
	Skåresågen	6592877	1366113	sawmill / wood impregnation	2	2
	Karlstads Gasverk 2, Klaraborg	6586620	1368310	gaswork (closed; <40Mm^3 gas produced 1867-1938)	2 (sil/sa)	-
	Yttre Hamnen	6585620	1370000	gaswork / tier	2	1
	Batteri-Branza, Örsholmen	6586410	1371920	engineering/accumulator industry	2	2
	Branza, Tormestad	6586840	1370700	engineering/accumulator industry	2 (si/sa)	2
	Bycosin	6586850	1371030	petrol station / organic chemical industry (active since 1940s)	1 (clay)	-
	Blåklockan 14 Karlstads Spinneri	6586410	1367830	textile industry	2	2
	Oldham industribatterier	6585096	1372031	accumulator industry	2	4
	kv Sälgen Karlstad Yllefabrik	6586550	1368080	spinnery	2	4
	Sköldpaddan 6	6586870	1369740	-	2	4
	Klaraviks Tricotfabrik	6586560	1367633	dry cleaning / textile industry (closed; active pre1890-~1980)	1 (si/sa)	2
	Skogaholmstvätten, Råtorp	6590562	1368303	dry cleaning (closed; chemical dry cleaning 1934-1989)	2	1
	Karlstad Glasbruk	6586110	1369663	glass industry (closed; active 1897-1929. Remediation measures undertaken)	1	-
	Orrholmens Såg	6585381	1368965	sawmill (closed; active pre1870-~1957)	1 (clay)	3
	Tullholmens Såg	6585711	1369147	sawmill (closed; active 1875-1940. Remediation measures undertaken)	1 (clay)	3
	Älvgatans Kemtvätt	6586688	1368464	dry cleaning (closed; active pre1954-1992)	1 (clay)	3
	Haga Press & Kemiska Tvätt	6586830	1369675	dry cleaning / textile industry	2	3
	Johanssons Kemiska Tvätt	6589390	1368868	dry cleaning (closed; active 1940-early 60s)	1	2
	Vic Självkem	6586819	1369798	dry cleaning	2	4
	Karlstad Garderobfärgeri & Kemiska Tvätt	6586710	1367775	dry cleaning / textile industry	2	3
	Kemiska Tvättinrättningen (1)	6586655	1369337	dry cleaning	2	3
	Karlstad Kemiska Tvätt	6586277	1371886	dry cleaning	2	3
	Nya Kemiska Tvätten (1)	6587328	1370128	dry cleaning (closed; active 1950s-~76)	1 (si/sa)	3
	Tingvalla Kemiska Tvättinrättning	6586575	1368975	dry cleaning	2	3
	Skogaholmstvätt	6586544	1368844	dry cleaning	2	3
	Sol-Tvätt (m.fl.)	6586882	1369164	dry cleaning	2	3
	Tvätt och Press (m.fl.)	6586732	1369555	dry cleaning (closed)	1 (si/sa)	4
	Nya Kemiska Tvätten (2)	6586129	1368972	dry cleaning	2	3
	Branza, Sågverksgatan	6586606	1371316	accumulator industry (closed; lead refining and –battery refining 1950s-60s)	1 (clay)	2
	STAWE Trikåfabrik	6586575	1369148	textile industry	2	4
	Karlstads Nya Läderfabrik	6586995	1369623	tannery / engineering industry (closed; active ~1860-1975)	1 (clay)	3
	A W Anderssons Trikåfabrik	6587584	1369306	textile industry	2	3
	Svenska Tagelspinneriet AB	6587377	1370460	textile industry	2	3
	Lindgrens Läderfabrik	6586991	1369877	tannery (closed; active 1866-~1940)	1 (clay)	2

Information tability zones/environmentally hazardous facilities/sites of potential/established soil contamination from the County Administrative Board of Värmland (2009a, b).

Appendix 1c
Risk objects along studied reaches of Ångermanälven

Environmental hazardous facilities and sites of potential/established soil contamination within
(i) 100 meters distance of the river course, and,
(ii) stability zone 1 or 2 (in Kramfors Municipality).

	Name	Location x	Location y	Type of facility/activity responsible (status/detailed)	Stability zone (detailed)	MIFO-class
Environmentally hazardous facilities	Lugnviks reningsverk	6981350	1606900	wastewater treatment plant	1 (clay>1:10)	
	Lugnviks sågverk/SCA Forest and Timber	6980680	1607460	sawmill	2 (clay<1:10)	
	Lunde reningsverk	6975381	1604928	wastewater treatment plant	2 (clay<1:10)	
	Mondi Dynäs AB	6986330	1597290	pulp/paper mill (active since 1894; 2006 production = 230 000t)	1 (clay>1:10)	
	Nordfabro AB	6982194	1599833	plastic manufacturing industry	2 (clay<1:10)	
	Nylands avloppsreningsverk	6988955	1599354	wastewater treatment plant	2 (silt/sand<1:n)	
	Sandslåns Reningsverk	6990510	1601510	wastewater treatment plant	2 (clay<1:10)	
Sites of established/potential soil contamination	Bollstasågen	6988320	1595380	sawmill // tier // metallurgic industry // foundry (active sawmill onsite; impregnation 1949-68)	1 (clay>1:10)	-
	Lugnviks sågverk	6980680	1607460	sawmill (active since 1873; impregnation 1935-60)	2 (clay<1:10)	-
	Kramforsviken	6982809	1600914	multiple (e.g. sawmill w wood impregnation, car care facility, engineering industry)	1 (clay>1:10) // 2 (silt/sand on clay<1:10 / silt/sand>1:n)	1
	Väja sulfatfabrik/pappersbruk	6986729	1596326	sawmill // paper/pulp mill (active mill on site (Mondi Dynäs AB); impregnation 1965-early 70s)	1 (clay>1:10)	-
	Skärsvikens sågverk	6979474	1601219	sawmill (closed; active 1885-1923)	1 (clay>1:10)	-
	Tollboms såg/Rossö östra	6988984	1599442	sawmill (active wastewater treatment plant onsite (Nyland, see above); sawmill 1894-1923)	2 (silt/sand<1:n)	-
	Nordfarbo AB	6992194	1599833	engineering industry (active, see above)	2 (clay<1:10)	-
	Lugnviks virkesmätningsplats	6981490	1606908	wood measuring (closed)	2 (clay<1:10)	-
	Sandslån	6990311	1600907	sorting works // car care facility (closed; active ?- late 1970. Some remediation measures undertaken)	2 (silt/sand<1:n)	-
	Lunde varv	6976106	1605288	tier // car care facility (closed)	2 (clay<1:10)	-
	Lunde reningsverk	6975381	1604928	wastewater treatment plant (active, see above)	2 (clay<1:10)	-
	Wedins skofabrik nr 2	6989977	1599350	shoe factory // tannery (closed; active 1956-65)	1 (clay>1:10)	-
	Gamla konsum/tryckeri	6989916	1599378	printing works (closed; active ?-1979)	1 (clay>1:10)	-
	Danielssons tryckeri 1	6989882	1599413	printing works (closed; active ?-1939)	1 (clay>1:10)	-
	Danielssons tryckeri 2	6990135	1599212	printing works (closed; active 1939-50)	2 (silt/sand<1:n)	-
	Nynäs	6990170	1599232	petrol station (closed)	2 (silt/sand<1:n)	-
	Hamnen Nyland	6989684	1599487	tier (closed)	1 (clay>1:10)	-
	Bensinpump	6989995	1599334	petrol station (closed; active ?-1962)	1 (clay>1:10)	-
	Åbergs billackering	6989963	1599401	car care (painting) facility (closed; active ~1965-early 80s)	1 (clay>1:10)	-
	Lunde 102	6975600	1605110	waste landfill (closed; active ?-~1950)	2 (clay<1:10)	4
	Kaninholmen 211	6990545	1599272	waste landfill (closed; active ?-1955)	2 (silt/sand<1:n)	2
	Strömnäsviken	6976816	1604467	waste landfill (closed; active ?-1957)	1 (clay>1:10)	4
	Kyrkvikstippen	6980010	1601068	waste landfill (closed; active ?-1957)	1 (clay>1:10)	4
	Sandslån 301	6990450	1601100	waste landfill (closed; active 1955-pre1969)	2 (silt/sand<1:n)	4
	Nylands mekaniska verkstad AB	6989812	1599441	engineering industry (active)	1 (clay>1:10)	-
	Bil Nordlund	6990251	1599196	metallurgic industry / car care facility (active)	2 (silt/sand<1:n)	-
	Verkstad Nyland	6989824	1599391	engineering industry (active)	2 (clay<1:10)	-
	Unanders Motor AB	6991798	1600379	car care facility (active since 1948)	2 (silt/sand<1:n)	-

Geographic information on stability zones from MSB (2007). Information on environmentally hazardous facilities/sites of potential/established soil contamination from the County Administrative Board of Västernorrland (2009a, b).

Appendix 2

Inventory of relevant historical mass movement events

A review of those mass movements that during this study have been found to have affected one or many SWS *and for which those effects have been further documented.* References as footnotes.

Location			Description				Contaminant mobilization	Key Observations			
county	Name (yr)	SWS	type	dominant material(-s)	area/volume	cause(-s)		surging	damming	turbidity	other
Kalmar	Almviksraset (1886)[1]	Gamlebyviken (Baltic Sea)	earth slide	clay, fills (wharf area, brick yard)	~8 400 m²	movement along faults // joint dilation due to sudden temperature-changes // wind- & wave-erosion	suspected				- 6-15 metres *increase* in sea-depth over area of ~25000m² - Two fatalities
Jämtland	Tångböle (1995)[2]	Indalsälven	earth slide	clay, silt	~200 000 m³	extreme spring flood	suspected			y	See chapter 6.2.1
	Mörviksån (2003)[3]	Mörviksån, Åresjön	mult. earth slides & debris flow	clay, debris		rain // deforestation // river engineering works	suspected		y	y	- Dam burst. - Major stream flow increase (from 0,5 to 7 m³/s) and major infrastructural damage - Permanent damage to fishery
Stockholm	Södertälje Kanal (1916)[4]	Södertälje Kanal	rotational earth slide	clay, fills (wharf area)	~2 800 m³	rain // dredging	suspected	y	y		- Major surge and major destruction of opposite bank and infrastructure - One fatality
Södermanland	Vagnhärad (1997)[5]	Trosaån	rotational earth slide	clay	~12 000 m²	rain // drainage leaking // overloading			y		- Permanent lateral dislocation of stream channel - Infrastructural damage
Värmland	Vålbergs Bobinfabrik (1934)[6]	Norsälven	earth slide	clay, sand	~10 000 m³		suspected				- Reel factory and timber yard on site of slide
	Norsälven (1951)[7]	Norsälven	multiple earth slides/falls/ flows	clay, sand	multiple smaller (15-50 m in length)	stream bed erosion // river traffic			y	y	- Multiple observations of intensified wave, wind and stream (eddy) erosion of affected river banks
	Trossnäs (1969)[8]	Norsälven	rotational earth slide	clay	~100 000 m³	thaw // low water // dredging // transitory stresses from traffic		y	y	y	See chapter 6.2.3
	Bengtsbol (1983)[9]	Klarälven	earth slide	clay	~15 000 m²				y	y	- Damming caused reduction of river channel cross-section of up to 35% —> 56% increase in river flow - Observations of selective erosion
	Ambjörby (1995)[10]	Norsälven	earth slide/fall		100 m length	rain	suspected				- Chipboard factory's pumping station destroyed
Västerbotten	Ajaure (1947)[11]	Giebnjanjaure (lake)	debris slide	till					y	y	- Dammed masses formed permanent island - Long-term turbidity in river downstream
Västernorrland	Remsele (1859)[12]	Ångermanälven	translational earth slide	silt/fine sand				y			- House destroyed on opposite bank
	Sollefteå (1868)[13]	Ångermanälven	translational earth slide	silt/fine sand			suspected	y			- Surge observed 2 km downstream - Tannery on direct opposite bank damaged
	Remsele (1899)[14]	Ångermanälven	translational earth slide	silt/fine sand			suspected	y			- Steam saw mill on direct opposite bank damaged - Bridge destroyed
	Kyrkviken (1959)[15]	Ångermanälven	retrogressive earth sliide	clay, silt	600m length	overloading (waste, macadam, snow) // transitory stresses (train traffic) //leaching	suspected	y	y		- Slide-masses found to have moved 700 m:s along the bottom of the river
	Bruksnipan (1967)[16]	Ångermanälven	translational earth slide	silt/fine sand				y			- House on opposite bank taken by surge and transported 6km downstream
	Skedom (2000)[17]	Ångermanälven	translational earth slide	silt/fine sand	~10 000 m³				y	y	- ~92% of slide masses eroded after 5 yrs (possibly due to extreme flow-rates in 2001)
	Paramon 1 (2001)[18]	Paraån, Ångermanälven	translational earth slide	silt/fine sand				y			- Surge wave reflected and major damage along both river banks. Piers and boats destroyed and moved
	Paramon 2 (2001)[19]	Paraån, Ångermanälven	translational earth slide	silt/fine sand				y			- Surge wave reflected and major damage along both river banks. Piers and boats destroyed and moved
	Öd 3 (2000)[20]	Ångermanälven	translational earth slide	silt/fine sand				y		y	- Main surge ~1.5-2 m
	Öd 1 (2000)[21]	Ångermanälven	translational earth slide	silt/fine sand	~31 000m³	wind // rain // overloading	suspected	y	y	y	See chapter 6.2.2

Appendix 2

Inventory of relevant mass movement events (cont.)

Location			Description				Contaminant mobilization	Key Observations			
county	name (yr)	SWS	type	dominant material(-s)	area/volume	cause(-s)		surging	damming	turbidity	other
Västernorrland (cont.)	Öd 2 (2003)[22]	Ångermanälven	translational earth slide	silt/fine sand	~19 000 m^3				y		- ~23% of slide masses eroded after 2 yrs
Västra Götaland	Jordfallet (1150)[23]	Göta Älv	earth slide	clay	~510 000 m^2				y		- Almost complete damming of 500 m wide river —> Permanent dislocation of river channel
	Intagan (1624)[24]	Göta Älv	rotational earth slide	clay	~270 000 m^2	rain // thunderstorms // possible earthquake		y	y	y	- One of the largest mass movements in Swedish history. Complete damming of the Göta Älv and major damage several tens of kilometres downstream when dam-break followed
	Gesäter (1694)[25]	Örekilsälven	earh slide	clay		possible earthquake			y		- Complete damming and permanent dislocation of river channel
	Linnarhult (1730)[26]	Lärjeån	earth slide	clay	~500 000 m^2				y		- River dammed along 5 kilometres length - Opposite bank covered in up to 12 m of slide masses - Six weeks until considerable erosion was noted
	Kviberg (1892)[27]	Säveån	earth slide	clay	~35 000 m^2	explosion			y		- Almost complete damming
	Svartå Grindar (1913)[28]	Aspen (lake)	earth slide	clay, fills	~500 000 m^3			y	y		- Slide scar flooded —> 15 m deep bay was formed - Masses slid ~400 m along bottom of lake - Major infrastructural damage
	Säveån (1945)[29]	Säveån	rotational earth slide	clay	~2 700 m^2	streambed erosion		y	y		- Masses slid ~50 m up- and downstream and was pushed up against opposite bank - Complete damming initially, heavy erosion occured rapidly
	Sköttorp (1946)[30]	Lidan	rotational earth slide	clay	~500 000 m^3	dredging // explosion // overloading // leaching //thaw			y		- Slide masses pushed up against opposite bank. Damming for 800 metres length along river - Most displaced masses eroded after ~1.5 yrs - Permanent island formed —> permanent alterations of flow/erosion-patterns
	Surteskredet (1950)[31]	Göta Älv	rotational earth slide	clay	~4 000 000 m^3	train traffic // construc-tion works	suspected	y	y	y	- Channel bed was raised ~9.5 m over large area —> almost complete damming and major surge - Flows followed upon main movement - Major infrastructural damage - 140-150 m difference in (length of) movement noted
	Guntorp (1953)[32]	Göta Älv	rotational earth slide	clay, fills	~1 700 m^2				y		- 6-7 m ~vertical displacement of slide masses along main scarp
	Östra Stranden (1955)[33]	Viskan	earth slide	clay, sand	~2 400 m^2	overloading // rain			y		- Almost complete damming caused intense erosion along opposite bank
	Götaskredet (1957)[34]	Göta Älv	rotational earth slide	clay	~370 000 m^2	streambed erosion // overloading //leaching	suspected	y	y	y	See chapter 6.2.5
	Lannaån (1963)[35]	Lannaån	earth slide	clay	several thousand m^3				y		- River dammed over 60 m - Very limited erosion in spite of considerable stream power - Substantial deposition of material 150-200 m downstream
	Fröland (1973)[36]	Göta Älv	earth slide	clay	~450 000 m^3	rain // explosion		y	y		- Surge grew as water depth increased and threw slide masses up onto opposite bank
	Agnesberg (1993)[37]	Göta Älv	rotational earth slide	clay	~9 600 m^2	streambed erosion // river traffic // dred-ging // overloading	suspected		y	y	- See chapter 6.2.6
	Ballabo (1996)[38]	Göta Älv	rotational earth slide	clay	~7 500 m^2	river bank erosion // steep subaqueous slope // low water table // drainage	suspected		y		- Water depth reduced by ~5 m
	Sjuntorp (2007)[39]	Lillån	earth slide	clay	50 000 t	rain			y	y	- Permanent dislocation of stream channel
Östergötland	Valdemarsvik (1905)[40]	Valdemarsvik	earth slide	clay, fills		overloading // dry period followed by heavy rain					- Increase in depth immediately in front of slide scar - Dammed masses still present as overgrown island after 11 yrs
	Getåskredet (1918)[41]	Bråviken (Baltic Sea)	rotational earth slide	clay, fills	~3 500 m^2	rain					- Damming over 65 m long, 35 m wide half-circular area - Shearing observed - Major infrastructural damage and 41 fatalities (passing train)
	Yara (2007)[42]	Ståthögaviken	earth slide	clay, fills	~1 200 m^2	rain // draining // ship traffic erosion // overloading	established		y		See chapter 6.2.4

Appendix 2
Inventory of relevant mass movement events (references)

[1] County Administrative Board of Kalmar, 2008. *Yttrande över slutbetänkande av Klimat- och sårbarhetsutredningen* (SOU 2007:60). Kalmar: County Administrative Board of Kalmar

Geological Survey of Sweden, 1914. *Beskrivning till kartbladet Gamleby* (SGU Ser Aa 140). Stockholm: Geological Survey of Sweden. 117 pp.

Wide, Å., 1972. *Litteraturinventering av skred inträffade i Götaland till och med 1971.* Göteborg: Chalmers Tekniska Högskola, Göteborgs Universitet. 40 pp.

[2] Ekberg, L., Åkesson, O., Harrami, O. & Rundström, H., 1995. *Utvärdering av den kommunala räddningstjänsten i samband med översvämningarna våren 1995* (Observatörsrapport). Karlstad: Statens räddningsverk. 48 pp.

Nilsson, P., 2005. *En sedimentundersökning i Åresjön*. Unpublished report. Åre: County Administrative Board of Jämtland. 10 pp.

[3] Kirkegaard, N., 7th June 2003. Dyr nota efter rasen i Åre. *Svenska Dagbladet*, Stockholm

Nilsson, P., 2005. *En sedimentundersökning i Åresjön*. Unpublished report. Åre: County Administrative Board of Jämtland. 10 pp.Nilsson, P., 2005.

Rosenberg, P., 6th June 2003. Jordskred och vattenmassor. *Östersunds-Posten*, Östersund.

Rydell-Janson, E., 7th June 2003. Skador för miljoner vållades av lerfloden i Åre. *Länstidningen Östersund*, Östersund.

[4] Järnvägsstyrelsen, 1922. *Skredet vid Södertälje kanal under utvidgningen år 1916* (Meddelande från Kungliga Järnvägsstyrelsens geotekniska avdelning Nr 2). Stockholm: Kungliga Järnvägsstyrelsen. pp. 81-86.

[5] Andersson, H., Bengtsson, P.-E., Berglund, C., Larsson, R., Sällfors, G. & Öberg-Högsta, A.-L., 1998. *Skredet i Vagnhärad. Teknisk/ vetenskaplig utredning om skredets orsaker* (SGI Rapport Nr 56). Linköping: Swedish Geotechnical Survey. 125 pp.

[6] Geological Survey of Sweden, 2000. *Map of the Quaternary Deposits 10D Karlstad* NV (Ser Ae 140). Uppsala: Geological Survey of Sweden.

[7] Bjurström, G., 1952. *Utredning rörande erosions-, ras- och skredförhållandena i Norsälven mellan Edsvalla och utloppet i Vänern vid Älvenäs*. Unpublished report. Stockholm: Bjurströms Geotekniska Byrå.

[8] County Administrative Board of Värmland [VL], 1969. *Sammanträde med anledning av raskatastrof i Norsälven norr Norskyrka.* Unpublished promemoria and meeting protocols (12th-22nd April 1969). Vålberg: County Administrative Board of Värmland.

Ehlin, U. & Zachrisson, G., 1969. *Spridningen i Vänerns nordvästra del av suspenderat material från skredet i Norsälven i April 1969* (Serie Hydrologi Vol 7). Stockholm: Swedish Mete orological and Hydrological Institute. 15 pp.

Lindskog, G. & Wager, O., 1970. *Skredet i Norsälven vid Trossnäs, Värmlands Län, 12 april 1969.* Stockholm: Swedish Geotechnical Institute. 18 pp.

Sjöberg, V., 1969. *Norsälvens vatten och stränder*. Unpublished report. Vålberg.

[9] Swedish Geotechnical Institute [SGI], 2009. *Skreddatabas.* Unofficial database. Linköping: Swedish Geotechnical Institute.

Sundborg, Å., 1983. *Erosionsförhållandena längs Klarälven nära skredplatsen i Bengtsbol*. Uppsala: Uppsala Universitet. 9 pp.

[10] Ekberg, L., Åkesson, O., Harrami, O. & Rundström, H., 1995. *Utvärdering av den kommunala räddningstjänsten i samband med översvämningarna våren 1995* (Observatörsrapport). Karlstad: Statens räddningsverk. 48 pp.

[11] Rudberg, S., 1950. Ett par fall av skred och ravinbildning i Västerbottens fjälltrakter. *GFF 72*, 139-148.

[12-14]

Fredén, C., 1996. Erosionsrisker längs älvarna i Sollefteå Kommun. *SGU Rapporter och Meddelanden: Miljögeologi 85*, 23-28.

[15] Jerbo, A. & Sandegren, E., 1963. *Skredet i Kyrkviken vid Kramfors, 1-4 februari 1959: The landslide at Kramfors on the Kyrkviken* (Meddelande från Kungliga Järnvägsstyrelsens Geotekniska Avdelning Nr 7). Stockholm: Kungliga Järnvägsstyrelsen. 28 pp.

[16] Fredén, C., 1996. Erosionsrisker längs älvarna i Sollefteå Kommun. *SGU Rapporter och Meddelanden: Miljögeologi 85*, 23-28.

[17-22]

Svensson, T., Persson, H. & Midboe, F., 2006. *Effekter i Ångermanälven från skred i nipor nedströms Sollefteå: dokumentation och beräkningar*. Karlstad: Nätverket för älvsäkerhet, Karlstads universitet. 54 pp.

[23] Swedish Geotechnical Institute [SGI], 2009. *Skreddatabas.* Unofficial database. Linköping: Swedish Geotechnical Institute.

Wide, Å., 1972. *Litteraturinventering av skred inträffade i Götaland till och med 1971.* Göteborg: Chalmers Tekniska Högskola, Göteborgs Universitet. 40 pp.

[24] Järnefors, B., 1954. *Skredet vid Intagan år 1648* (SGU Ser C 48:4(539)). Stockholm: Geological Survey of Sweden. 18 pp.

[25] Wide, Å., 1972. *Litteraturinventering av skred inträffade i Götaland till och med 1971.* Göteborg: Chalmers Tekniska Högskola, Göteborgs Universitet. 40 pp.

[26] Melander, T. (ed.), 1997. *Göteborgs Geotekniska Historia - några sonderingar*. Göteborg: SGF Väst. 128 pp.

Swedish Geotechnical Institute [SGI], 2009. *Skreddatabas.* Unofficial database. Linköping: Swedish Geotechnical Institute.

[27, 28]

Wide, Å., 1972. *Litteraturinventering av skred inträffade i Götaland till och med 1971.* Göteborg: Chalmers Tekniska Högskola, Göteborgs Universitet. 40 pp.

[29] Caldenius, C., 1945. *Skredet vid Säveån den 18 Januari 1945* (SGU Ser C 39:9(476)). Uppsala: Geological Survey of Sweden. 13 pp.

Wide, Å., 1972. *Litteraturinventering av skred inträffade i Götaland till och med 1971.* Göteborg: Chalmers Tekniska Högskola, Göteborgs Universitet. 40 pp.

[30] Mohrén, E. & Larsson, W., 1974. *Beskrivning till kartbladet Levene* (SGU Ser Aa 201). Stockholm: Geological Survey of Sweden.

Odenstad, S., 1951. *The landslide at Sköttorp on the Lidan river February 2, 1946* (Royal Swedish Geotechnical Institute Proceedings Nr 4). Stockholm: Royal Swedish Geotechnical Proceedings. 40 pp.

[31] Jakobson, B., 1952. *The landslide at Surte on the Göta River* (Royal Swedish Geotechnical Institute Proceedings Nr 5). Stockholm: Royal Swedish Geotechnical Proceedings. 120 pp.

Melander, T. (ed.), 1997. *Göteborgs Geotekniska Historia - några sonderingar*. Göteborg: SGF Väst. 128 pp.

Wide, Å., 1972. *Litteraturinventering av skred inträffade i Götaland till och med 1971.* Göteborg: Chalmers Tekniska Högskola, Göteborgs Universitet. 40 pp.

[32, 33]

Wide, Å., 1972. *Litteraturinventering av skred inträffade i Götaland till och med 1971.* Göteborg: Chalmers Tekniska Högskola, Göteborgs Universitet. 40 pp.

[34] Melander, T. (ed.), 1997. *Göteborgs Geotekniska Historia - några sonderingar*. Göteborg: SGF Väst. 128 pp.

Odenstad, S., 1958. Jordskredet i Göta den 7e juni 1957. *GFF 492 (80)*, 76-86.

Wide, Å., 1972. *Litteraturinventering av skred inträffade i Götaland till och med 1971.* Göteborg: Chalmers Tekniska Högskola, Göteborgs Universitet. 40 pp.

[35] Hjort, S., 1964. *Skred och raviner längs Lidan*. Uppsala: Uppsala University. 45 pp.

[36] Bjurström, G., 1982. *Skredet vid Fröland.* Stockholm: Statens råd för byggnadsforskning, Stockholm, 40 pp.

[37] Larsson, R., Ottosson, E. & Sällfors, G., 1994. *Agnesbergsskredet* (SGI Rapport Nr 44). Linköping: Swedish Geotechnical Institute. 73pp.

[38] Andersson, H., Ottosson, E. & Sällfors, G., 1999. *Skredet i Ballabo, Västerlanda* (SGI Rapport Nr 53). Linköping: Swedish Geotechnical Institute. 7 pp.

Swedish Geotechnical Institute [SGI], 2009. *Skreddatabas.* Unofficial database. Linköping: Swedish Geotechnical Institute.

[39] Anderstedt, M.-L., 2007. *Stort ras i Sjuntorp*. TTELA, Sjuntorp.

Engblom, A., 25th January 2007. *Lillån rensas efter förra veckans jord skred*, TTELA, Sjuntorp.

[40] Geological Survey of Sweden, 1928. *Beskrivning till Kartbladet Valdemarsvik* (Ser Aa 158). Stockholm: Geological Survey of Sweden. 68 pp.

Wide, Å., 1972. *Litteraturinventering av skred inträffade i Götaland till och med 1971.* Göteborg: Chalmers Tekniska Högskola, Göteborgs Universitet. 40 pp.

[41] Järnvägsstyrelsen, 1922. *Skredet vid Vita Sikudden å bansträckan Nyköping-Norrköping år 1918* (Meddelande från Kungliga Järnvägsstyrelsens geotekniska avdelning Nr 2). Stockholm: Kungliga Järnvägsstyrelsen. pp. 69-76.

Swedish Geotechnical Institute [SGI], 2009. *Skreddatabas.* Unofficial database. Linköping: Swedish Geotechnical Institute.

[42] Lundgren, F., Forsberg, J. & Göransson, M., 2008. *YARA, Ståthögaviken, Norrköping. Miljöteknisk sedimentundersökning och ytvattenprovtagning*. Unpublished report. Malmö: WSP Environmental. 10 pp.

Persson, R., 2007. *PM angående skred vid Ståhögaviken*. Unpublished promemoria. Landskrona: Yara AB.

Persson, R., 2008. *PM angående jordskred inom fastigheten Slottshagen - Statusbeskrivning i februari 2008 och förslag till fortsatt handläggning*. Unpublished promemoria. Landskrona: Yara AB.

Tidigare skrifter i serien ”Examensarbeten i Geologi vid Lunds Universitet”:

205. Bergelin, Ingemar, 2006: $^{40}Ar/^{39}Ar$ geochronology of basalts in Scania, S Sweden: evidence for two pulses at 191-178 Ma and 110 Ma, and their relation to the break-up of Pangea.
206. Edvarssson, Johannes, 2006: Dendrokronologisk undersökning av tallbestånds etablering, tillväxtdynamik och degenerering orsakat av klimatrelaterade hydrologiska variationer på Viss mosse och Åbuamossen, Skåne, södra Sverige, 7300-3200 cal. BP.
207. Stenfeldt, Fredrik, 2006: Litostratigrafiska studier av en platåformad sand- och grusavlagring i Skuremåla, Blekinge.
208. Dahlenborg, Lars, 2007: A Rock Magnetic Study of the Åkerberg Gold Deposit, Northern Sweden.
209. Olsson, Johan, 2007: Två svekofenniska graniter i Bottniska bassängen; utbredning, U-Pb zirkondatering och test av olika abrasionstekniker.
210. Erlandsson, Maria, 2007: Den geologiska utvecklingen av västra Hamrångesynklinalens suprakrustalbergarter, centrala Sverige.
211. Nilsson, Pernilla, 2007: Kvidingedeltat – bildningsprocesser och arkitektonisk uppbyggnadsmodell av ett glacifluvialt Gilbertdelta.
212. Ellingsgaard, Óluva, 2007: Evaluation of wireline well logs from the borehole Kyrkheddinge-4 by comparsion to measured core data.
213. Åkerman, Jonas, 2007. Borrkärnekartering av en Zn-Ag-Pb-mineralisering vid Stenbrånet, Västerbotten.
214. Kurlovich, Dzmitry, 2007: The Polotsk-Kurzeme and the Småland-Blekinge Deformation Zones of the East European Craton: geomorphology, architecture of the sedimentary cover and the crystalline basement.
215. Mikkelsen, Angelica, 2007: Relationer mellan grundvattenmagasin och geologiska strukturer i samband med tunnelborrning genom Hallandsås, Skåne.
216. Trondman, Anna-Kari, 2007: Stratigraphic studies of a Holocene sequence from Taniente Palet bog, Isla de los Estados, South America.
217. Månsson, Carl-Henrik & Siikanen, Jonas, 2007: Measuring techniques of Induced Polarization regarding data quality with an application on a test-site in Aarhus, Denmark and the tunnel construction at the Hallandsås Horst, Sweden.
218. Ohlsson, Erika, 2007: Classification of stony meteorites from north-west Africa and the Dhofar desert region in Oman.
219. Åkesson, Maria, 2008: Mud volcanoes - a review. (15 hskp)
220. Randsalu, Linda, 2008: Holocene relative sea-level changes in the Tasiusaq area, southern Greenland, with focus on the Ta1 and Ta3 basins. (30 hskp)
221. Fredh, Daniel, 2008: Holocene relative sea-level changes in the Tasiusaq area, southern Greenland, with focus on the Ta4 basin. (30 hskp)
222. Anjar, Johanna, 2008: A sedimentological and stratigraphical study of Weichselian sediments in the Tvärkroken gravel pit, Idre, west-central Sweden. (30 hskp)
223. Stefanowicz, Sissa, 2008: Palynostratigraphy and palaeoclimatic analysis of the Lower - Middle Jurassic (Pliensbachian - Bathonian) of the Inner Hebrides, NW Scotland. (15 hskp)
224. Holm, Sanna, 2008: Variations in impactor flux to the Moon and Earth after 3.85 Ga. (15 hskp)
225. Bjärnborg, Karolina, 2008: Internal structures in detrital zircons from Hamrånge: a study of cathodoluminescence and back-scattered electron images. (15 hskp)
226. Noresten, Barbro, 2008: A reconstruction of subglacial processes based on a classification of erosional forms at Ramsvikslandet, SW Sweden. (30 hskp)
227. Mehlqvist, Kristina, 2008: En mellanjurassisk flora från Bagå-formationen, Bornholm. (15 hskp)
228. Lindvall, Hanna, 2008: Kortvariga effekter av tefranedfall i lakustrin och terrestrisk miljö. (15 hskp)
229. Löfroth, Elin, 2008: Are solar activity and cosmic rays important factors behind climate change? (15 hskp)
230. Damberg, Lisa, 2008: Pyrit som källa för spårämnen – kalkstenar från övre och

mellersta Danien, Skåne. (15 hskp)

331. Cegrell, Miriam & Mårtensson, Jimmy, 2008: Resistivity and IP measurements at the Bolmen Tunnel and Ådalsbanan, Sweden. (30 hskp)

232. Vang, Ina, 2008: Skarn minerals and geological structures at Kalkheia, Kristiansand, southern Norway. (15 hskp)

233. Arvidsson, Kristina, 2008: Vegetationen i Skandinavien under Eem och Weichsel samt fallstudie i submoräna organiska avlagringar från Nybygget, Småland. (15 hskp)

234. Persson, Jonas, 2008: An environmental magnetic study of a marine sediment core from Disko Bugt, West Greenland: implications for ocean current variability. (30 hskp)

235. Holm, Sanna, 2008: Titanium- and chromium-rich opaque minerals in condensed sediments: chondritic, lunar and terrestrial origins. (30 hskp)

236. Bohlin, Erik & Landen, Ludvig, 2008: Geofysiska mätmetoder för prospektering till ballastmaterial. (30 hskp)

237. Brodén, Olof, 2008: Primär och sekundär migration av hydrokarboner. (15 hskp)

238. Bergman, Bo, 2009: Geofysiska analyser (stångslingram, CVES och IP) av lagerföljd och lakvattenrörelser vid Albäcksdeponin, Trelleborg. (30 hskp)

239. Mehlqvist, Kristina, 2009: The spore record of early land plants from upper Silurian strata in Klinta 1 well, Skåne, Sweden. (45 hskp)

239. Mehlqvist, Kristina, 2009: The spore record of early land plants from upper Silurian strata in Klinta 1 well, Skåne, Sweden. (45 hskp)

240. Bjärnborg, Karolina, 2009: The copper sulphide mineralization of the Zinkgruvan deposit, Bergslagen, Sweden. (45 hskp)

241. Stenberg, Li, 2009: Historiska kartor som hjälp vid jordartsgeologisk kartering – en pilotstudie från Vångs by i Blekinge. (15 hskp)

242. Nilsson, Mimmi, 2009: Robust U-Pb baddeleyite ages of mafic dykes and intrusions in southern West Greenland: constraints on the coherency of crustal blocks of the North Atlantic Craton. (30 hskp)

243. Hult, Elin, 2009: Oligocene to middle Miocene sediments from ODP leg 159, site 959 offshore Ivory Coast, equatorial West Africa. (15 hskp)

244. Olsson, Håkan, 2009: Climate archives and the Late Ordovician Boda Event. (15 hskp)

245. Wollein Waldetoft, Kristofer, 2009: Svekofennisk granit från olika metamorfa miljöer. (15 hskp)

246. Månsby, Urban, 2009: Late Cretaceous coprolites from the Kristianstad Basin, southern Sweden. (15 hskp)

247. MacGimpsey, I., 2008: Petroleum Geology of the Barents Sea. (15 hskp)

248. Jäckel, O., 2009: Comparison between two sediment X-ray Fluorescence records of the Late Holocene from Disko Bugt, West Greenland; Paleoclimatic and methodological implications. (45 hskp)

249. Andersen, Christine, 2009: The mineral composition of the Burkland Cu-sulphide deposit at Zinkgruvan, Sweden – a supplementary study. (15 hskp)

250. Riebe, My, 2009: Spinel group minerals in carbonaceous and ordinary chondrites. (15 hskp)

251. Nilsson, Filip, 2009: Föroreningsspridning och geologi vid Filborna i Helsingborg. (30 hskp)

252. Peetz, Romina, 2009: A geochemical characterization of the lower part of the Miocene shield-building lavas on Gran Canaria. (45 hskp)

253. Maria Åkesson, 2010: Mass movements as contamination carriers in surface water systems – Swedish experiences and risks. (45 hskp)

254. Elin Löfroth, 2010: A Greeland ice core perspective on the dating of the Late Bronze Age Santorini eruption. (45 hskp)

LUNDS UNIVERSITET

Institutionen för geo- och ekosystemvetenskaper
Enheten för geologi
Sölvegatan 12, 223 62 Lund