Swedish Geotechnical Institute

Landslide risks in the Göta River Valley in a changing climate

Final report
Part 1 - Societal consequences

GÄU
The Göta River investigation
2009 - 2011

Linköping 2012

Göta River investigation
Final report, Part 1

Order

Photos on the cover

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Preface

In 2008, the Swedish Government commissioned the Swedish Geotechnical Institute (SGI) to conduct a mapping of the risks for landslides along the entire river Göta älv (hereinafter called the Göta River) - risks resulting from the increased flow in the river that would be brought about by climate change (M2008/4694/A). The investigation has been conducted during the period 2009-2011. The date of the final report has, following a government decision (17/11/2011), been postponed until 30 March 2012.

The assignment has involved a comprehensive risk analysis incorporating calculations of the probability of landslides and evaluation of the consequences that could arise from such incidents. By identifying the various areas at risk, an assessment has been made of locations where geotechnical stabilising measures may be necessary. An overall cost assessment of the geotechnical aspects of the stabilising measures has been conducted in the areas with a high landslide risk. Furthermore, an overall assessment of the geotechnical preconditions for increased flow in the Göta River is also presented.

The investigation has primarily been conducted by SGI employees. The work has been led by SGI's management group, under the leadership of the Director General, Birgitta Boström. The work has been organised into one main assignment for the project management and into a large number of sub-assignments, as far as method development and investigation are concerned. SGI has utilised the support of a number of agencies and research institutions, including the Swedish Meteorological and Hydrological Institute (SMHI), the Geological Survey of Sweden (SGU), Chalmers University of Technology, Lund University, the University of Stuttgart, the Norwegian Geotechnical Institute (NGI), Vattenfall, the Swedish Maritime Administration and the Swedish Transport Administration. All municipalities within the Göta River valley and the County Administrative Board of Västra Götaland have also participated at various stages of the project. Finally, SGI has engaged a large number of consultants, primarily from the Göteborg region, as extra resources in the implementation of the investigative work.

The results and conclusions of the investigation are presented in a final report, *Landslide risks in the Göta River valley in a changing climate.* The report consists of three parts:

Final report, Part 1 – Societal Consequences, which comprises a summary of the assignment, landslide risks and the consequences for society, the costs of measures and the proposals of the investigation with regard to future activities. Part 1 is aimed primarily at those who require an overall description of the landslide risks that exist in the valley, how these may affect the local community and the measures that need to be taken.

Final report, Part 2 – Mapping, which comprises a description of the investigation's methodology, inventories, field and laboratory investigations, calculations and analyses. The target group for Part 2 is those who wish to delve deeper into the investigation and acquire more detailed facts regarding the various conditions in the valley, as a basis for planning and adapting to climate change.

Final report, Part 3 – Maps, which comprises an account of the landslide risks for various parts of the Göta River, in map form. Part 3 describes where along the river the landslide risks can be found and the areas that would be affected. The maps also contain a classification of the climatic impact along the river.

In addition to the final report, the detailed work involved with the taking of inventories, method development and analyses has also been described in 34 interim reports that were submitted to the government on 21/12/2011. The reports are listed in the Appendix and are available via SGI's website: *www.swedgeo.se*

Final report, Part 2 has been edited by Karin Lundström and Bengt Rydell. Text has been submitted by Yvonne Andersson-Sköld, Per-Evert Bengtsson, Charlotte Cederbom, Stefan Falemo, Gunnel Göransson, Bo Lind, Karin Lundström, Hjördis Löfroth, Håkan Persson, Bengt Rydell, Hanna Tobiasson-Blomén, Marius Tremblay, Helen Åhnberg and Mats Öberg. The checking of technical details has been conducted by Rolf Larsson. Elin Sjöstedt has been responsible for layout and proofreading has been conducted by Per Samuelson and Anders Salomonson.

This is a translation from the Swedish original and the SGI may not be claimed responsible for any misunderstanding or error that may occur from the translation.

Linköping, March 2012

Bo Lind
Acting Director General

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The main proposal of the Göta River investigation

The investigation has demonstrated that there are many areas within the Göta River valley that have a high landslide risk under the current conditions, and that these risks will increase as the climate changes. The change in the climate means that the risk of landslides will increase for about 25 % of the mapped areas up until the year 2100, if no measures are taken.

Landslides can affect many different aspects of life along the Göta River, including residential areas and important social functions such as roads, railways, shipping, water and electricity supply plants. To this can be added a long list of other consequences for the communities and their residents.

In the light of the large human, financial and environmental aspects that are affected along the Göta River, the investigation concludes that it is necessary, and geotechnically possible, to take action so that drainage through the river can be increased, at the same time as the risk of landslides is reduced.

The measures should be implemented in order to reduce the probability of landslides given the current conditions, at the same time helping to prevent risks arising from increased flow in the future. Measures should be taken first in prioritised areas, where there is a high risk of landslides in close proximity to the river. The cost of measures in these areas has been estimated at between SEK 4-5 billion with current flow levels, and SEK 5-6 billion with increased flow levels brought about by the future change in climate.

SGI proposes that:

1. Measures be taken to adapt the Göta River valley to increased levels of flow
2. A delegation for climate adaptation be appointed for the Göta River valley

1. Adapting the Göta River valley for increased levels of flow

Current levels of risk should be reduced through the implementation of geotechnical measures in prioritised areas. The measures will be effective both in terms of meeting the demands of climate change and in reducing the current risk of landslides.

There is a need to **improve and stabilise the erosion protection** along the shores of the river. Furthermore, it is proposed that specific surveillance of erosion should be introduced in areas that currently have a high risk of landslides, as well as in areas that are subject to large climatic impact.

Geotechnical stabilising work should be coordinated with physical planning. Extensive stabilising measures will require specific provisions in the municipality development plans of several areas. Permission from the Land and Environment Courts will probably be required for most of the activities. In order to handle this in a time and resource-efficient manner, it is proposed that the stabilising measures are planned and prioritised comprehensively for the entire river.

2. A delegation for climate adaptation

SGI proposes that a **delegation be appointed to work with sustainable climate adaptation in the Göta River valley.** The aim of the delegation is to co-ordinate, plan and implement measures that reduce the risk of landslides for existing residential areas and infrastructures, and to prevent the risk of landslides for new developments, based on the current climate and that for the future. The delegation should be composed of representatives from various concerned public interest groups. An established core of permanent members is required for continuity and general viewing, and we propose that the delegation also should have a political linking. The delegation should have specific government funding at its disposal, intended for the implementation of tangible adaptation measures in the Göta River valley.

1 The assignment

1.1 The Government's commission

In 2008, the Swedish Government, in the letter of appropriations (M2008/4694/A) commissioned SGI to perform a mapping of the risks for landslides along the entire Göta River resulting from the increased flow in the river brought about by climate change. The investigation has been conducted during the period 2009-2011. The date for the final report has, following a government decision (17/11/2011), been postponed until 30 March 2012.

The letter of appropriations issued the following directions in connection with the assignment:

“In order to address forthcoming climate changes and handle increased flow in the Göta River, greater understanding is required of the stability conditions along the entire Göta River. The funding is to be used for the improvement and production of landslide analyses and stability mapping along the Göta River.”

SGI has performed the assignment by:

- Conducting and presenting a comprehensive analysis of the risks for landslides along the Göta River and part of the Nordre River. The analysis has involved the collection of data, calculations of the probability of landslides, and evaluations of the consequences that could arise from landslides. The risks included the conditions that apply based on the current climate and those that can be expected to apply in the year 2100.

- Carrying out method developments in order to improve and make more effective previously produced methods used for landslide risk analyses.

- Assess where geotechnical stabilising measures may be necessary and provide an overall assessment of their cost.

New and developed methods have been produced in order to improve landslide risk analyses and stability calculations, to improve knowledge of the erosion processes along the Göta River, to assess the effect of climate changes on groundwater conditions, to develop methodologies for mapping and the handling of highly sensitive clay (quick clay), and for consequence assessment. The investigation has been conducted in coordination with other agencies, research institutions, and national and international organisations. The work has involved the most extensive mapping of landslide risks conducted in Sweden.

1.2 Background

The ongoing global climate change is affecting the conditions for residential developments and infrastructure in many ways. The final report of the Swedish Commission on Climate and Vulnerability (Klimat- och sårbarhetsutredningen, 2007) highlighted the fact that the risks for flooding, landslides and erosion will increase in many parts of Sweden and that preventative measures are necessary. The Commission's interim report (Klimat och sårbarhetsutredningen, 2006), which deals with the risks for Mälaren, Hjälmaren and Vänern, points out the need for increased drainage through the Göta River due to increased inflow into Lake Vänern. In a previous government commission given to SGI, an action plan developed to predict and prevent natural disasters in Sweden in the event of climate change, SGI reported that increased drainage could lead to increased erosion and, consequently, an increased risk of landslides along the river (SGI, 2006). The action plan also states that the climate changes will lead to changes in the groundwater conditions in the soil layers along the river, something which in turn can lead to a decreasing stability of the slopes along the Göta River.

The Göta River is one of the country's largest water courses and the river valley is characterised by varied countryside that has been formed through natural erosion and landslide processes. A number of landslides of varying sizes occur along the river every year, and landslides are much more common in this area than in other parts of the country. The primary reasons for the high frequency of landslides in the Göta River valley are its geological formation, with immense, soft clay layers that were once deposited in a marine environment, the varying flow within the river which causes erosion, and the effect of the expansion and activities of the society that surrounds it. The river is an important traffic corridor that has provided the preconditions for the establishment of ports, industry, housing and infrastructure. These establishments mean that the consequences of landslides would be large at several locations along the river valley, since housing, industry, roads, railways and maritime traffic would be affected. Furthermore, polluted soil would become involved and there might be an adverse effect on water intake.

The type of landslide that occurs in the Göta River valley is primarily a sliding of fine-grained soil composed of clay and silt. This type of landslide typically occurs suddenly and without any distinct visible warning signs. However, sometimes soil subsidence and cracks in the ground can appear as indicators of an imminent landslide. When a landslide occurs, the soil breaks up and starts moving quickly. Depending on the nature of the landslide, the soil masses which were originally connected to each other can break up into large chunks or slabs and become more or less fluid and travel great distances. Landslides can occur both above and below the river's water surface.

Changes in climate mean an increase in the risk of natural disasters. In order to limit the damage and address the new preconditions that are implied by climate change, it is important not only to identify risks and protect exposed areas and existing structures, but also to improve the quality of planning for future residential developments and infrastructures, taking the climate of the future into consideration.

1.3 The scope of the assignment and its limitations

The area of investigation stretches from the power plant at Vargön in Vänersborg to the Marieholm Bridge in Göteborg, as well as the stretch along the Nordre River as far as the Kornhall ferry berth in the municipality of Kungälv, see Figure 1-1. In total, this encompasses a stretch of approximately 100 km with a corresponding shoreline of 200 km. The width of the investigation area is limited to those areas that could be affected by primary and secondary landslides in connection with the Göta River. Investigations of the tributaries are limited to stretches in the vicinity of the river or areas where landslides could affect the Göta River's discharge capacity.

In parallel with SGI's mapping, the City of Göteborg performed detailed stability investigations within Göteborg Municipality's urban areas. SGI and the City of Göteborg have collaborated closely while the work has been in progress and had a mutual exchange of material and information. Through a collaborative agreement, the results from Göteborg's stability investigations have also been used in SGI's landslide risk mapping.

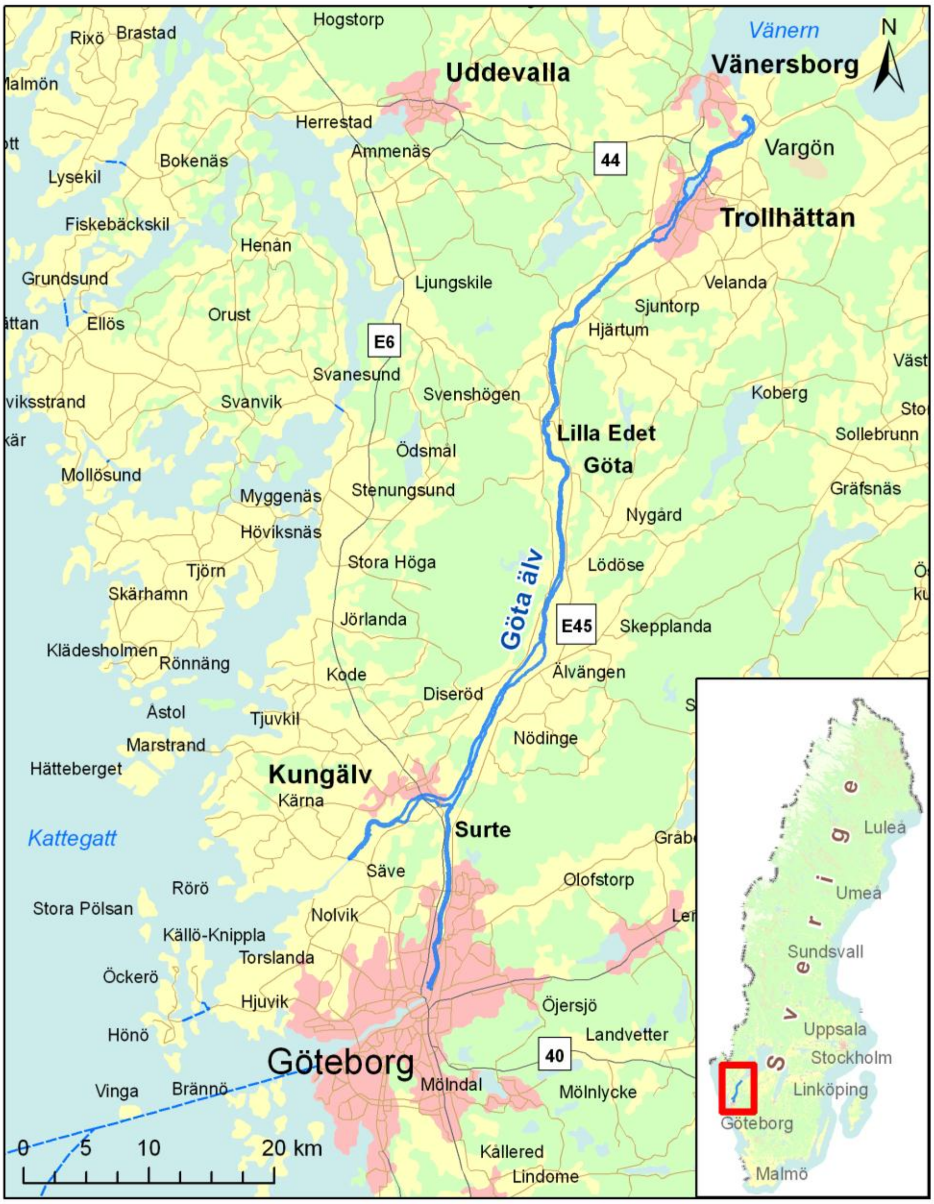

Figure 1-1
Area of investigation – the Göta River investigation.
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1.4 How the assignment has been performed

Landslide risk analysis

The geological conditions in the Göta River valley vary greatly, as does the topography of the valley and neighboring areas. The slope stability and the probability of landslides can therefore vary greatly within two closely connected areas. In order to obtain a true and correct picture of the risk of landslides, good knowledge is therefore required of the soil conditions and the ground's geotechnical consistency, in addition to considerable awareness of the threatened natural values and the consequences that landslides can imply.

The assignment involved a comprehensive risk analysis incorporating calculations of the probability of landslides, and evaluations of the consequences that could arise from such incidents. By identifying the various areas at risk, an assessment has been made of locations where geotechnical stabilising measures may be necessary. An overall cost assessment of the geotechnical aspects of the stabilising measures, based on reliable methods, has been conducted in the areas with a high landslide risk. Finally, an overall assessment of the geotechnical preconditions for increased flow in the Göta River is also presented.

Development work

Whilst planning the assignment, it became evident that there was a need for method development and the improvement of knowledge, with regard to both the mapping of the parameters incorporated and for the analysis on which the risk assessment was to be based. SGI therefore incorporated method development into the investigation at an early stage, in order to streamline and improve the work that was to follow, see section 1.5.

The development work connected with the assignment has been needs-based and provided direct support to the work of the investigation. Furthermore, much of this work has also resulted in the acquisition of valuable knowledge that can be utilised in other applications and areas.

Dialogue and cooperation

Broad cooperation and dialogue with other organisations have been central to the assignment throughout the whole investigation period. To this end, an interest group was linked to the investigation, consisting of representatives from the Swedish Maritime Administration, the Swedish Transport Administration, Vattenfall, the Swedish Civil Contingencies Agency (MSB), the Geological Survey of Sweden (SGU), the Swedish Meteorological and Hydrological Institute (SMHI), the County Administrative Board of Västra Götaland and all of the municipalities located along the Göta River.

Information has been exchanged throughout the whole assignment, and there has been dialogue and consultation between the County Administrative Board of Västra Götaland and all the municipalities located along the Göta River valley - Vänersborg, Trollhättan, Lilla Edet, Ale, Kungälv and Göteborg. Close collaboration and contact has also been maintained with the Swedish Maritime Administration and Vattenfall, whose operations are directly connected to the river. Furthermore, there has been specific dialogue with the Swedish Transport Administration due to the ongoing investigations of the road E45 and the Norway-Vänern railwayline, and with the City of Göteborg, with the aim of coordinating the stability investigations along the sections of the Göta River that lie within the municipality of Göteborg.

External experts have participated in various development projects and have also been involved in the examination of the analysis methods produced.

1.5 Organisation and working methods

The investigation has been led comprehensively by SGI's management group and a specific management committee, both of which were under the management of the Institute's Director General. A project management group, led by Marius Tremblay (also leader of the main assignment), has been responsible for the operational management of the investigation.

The assignment was divided up into one main assignment for comprehensive issues, project management and administration, and a number of sub-assignments for specific activities such as the taking of data inventory, method development, investigations and analyses. Internal support functions within the areas of finance, CAD/GIS and IT have assisted during the investigation. Figure 1-2 presents the organisational chart for the Göta River investigation.

The investigatory and development work has been performed in nine different special investigations that, above all, have been aimed at the development of methodology, the inventorying of previous investigations and the analysis of climate changes. A large number of employees at SGI and various external operators have been involved in the development work, something which is evident from the interim reports in the Appendix. For a more detailed description of the working relationships described in this Final report, Part 1, refer to the interim reports and the Final report, Part 2 and Part 3.

Preparatory work was initially performed in the assignment, involving the management of digital data. Amongst other things, a web-based mapping application was developed for the Göta River valley and approximately 18,000 geotechnical investigation points that had previously been investigated in the area were collated and structured so that they could be used as data for the investigation.

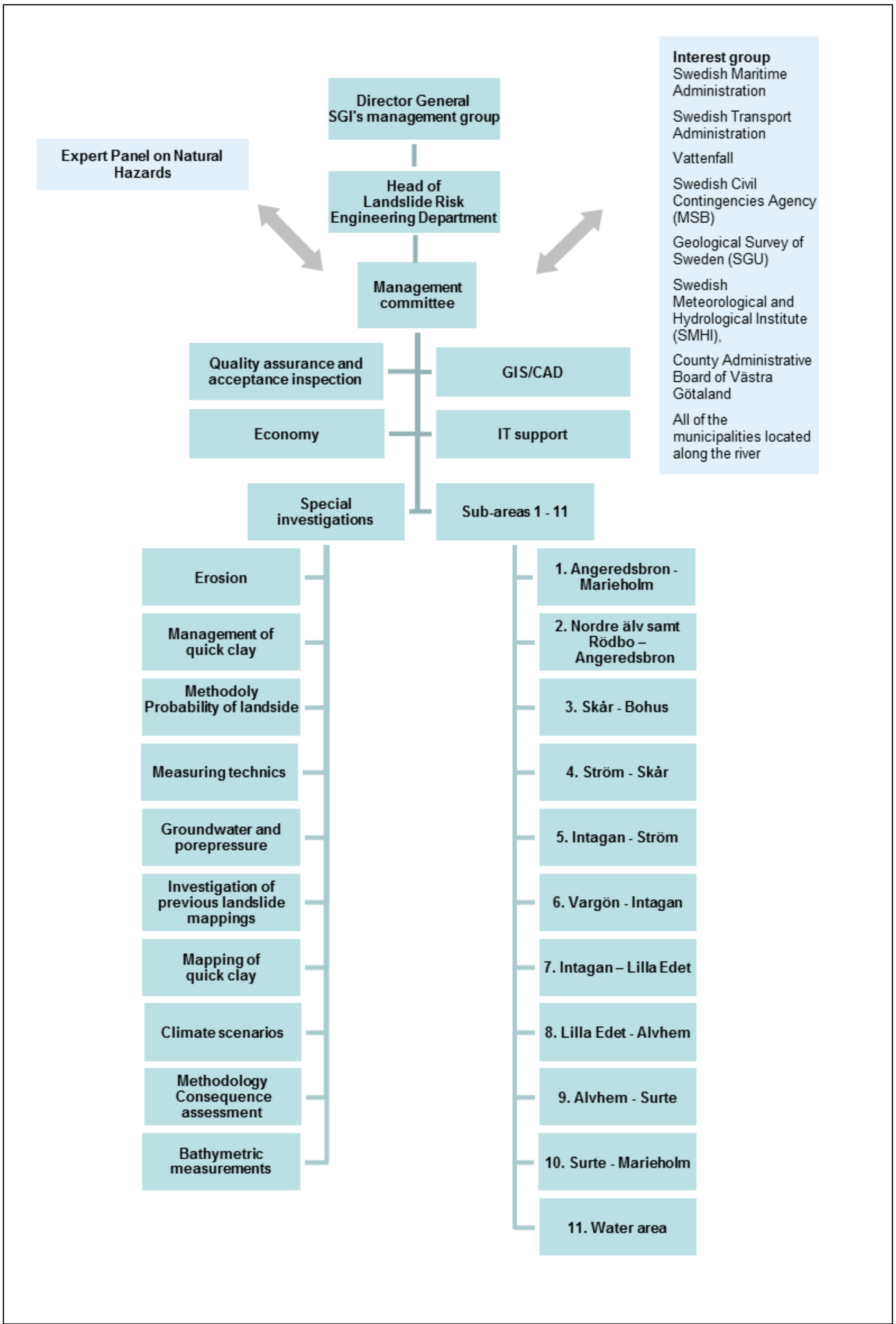


Figure 1-2 *Organisational chart for the Göta River investigation.*

The area of investigation has been divided into ten geographical sub-areas on land and one area within the river, see Figure 1-3. The division was made according to a demarcation of appropriate terrain of suitable size for the respective area.

Geotechnical investigations in the field and the laboratory have been conducted within all of the sub-areas and have included probing and sampling at specific points and in sections across the river. Based on the data obtained, analyses of slope stability have been conducted in approximately 240 sections (of 100-400m in length), the majority of which lay at right angles to the river. The assignment has involved the processing of a large amount of geotechnical field data and calculations. Around 2,500 geotechnical field investigations (probing, sampling, etc.) have been conducted. Furthermore, more than 4,000 soil and sediments samples have been examined, involving approximately 20,000 laboratory tests.

A special control group has been established for the inspection and quality assurance of the work carried out by SGI's own personnel or by external consultants. The inspection has been carried out in accordance with established instructions and, following their inspection, the reports have been corrected and the results passed on within the investigation.

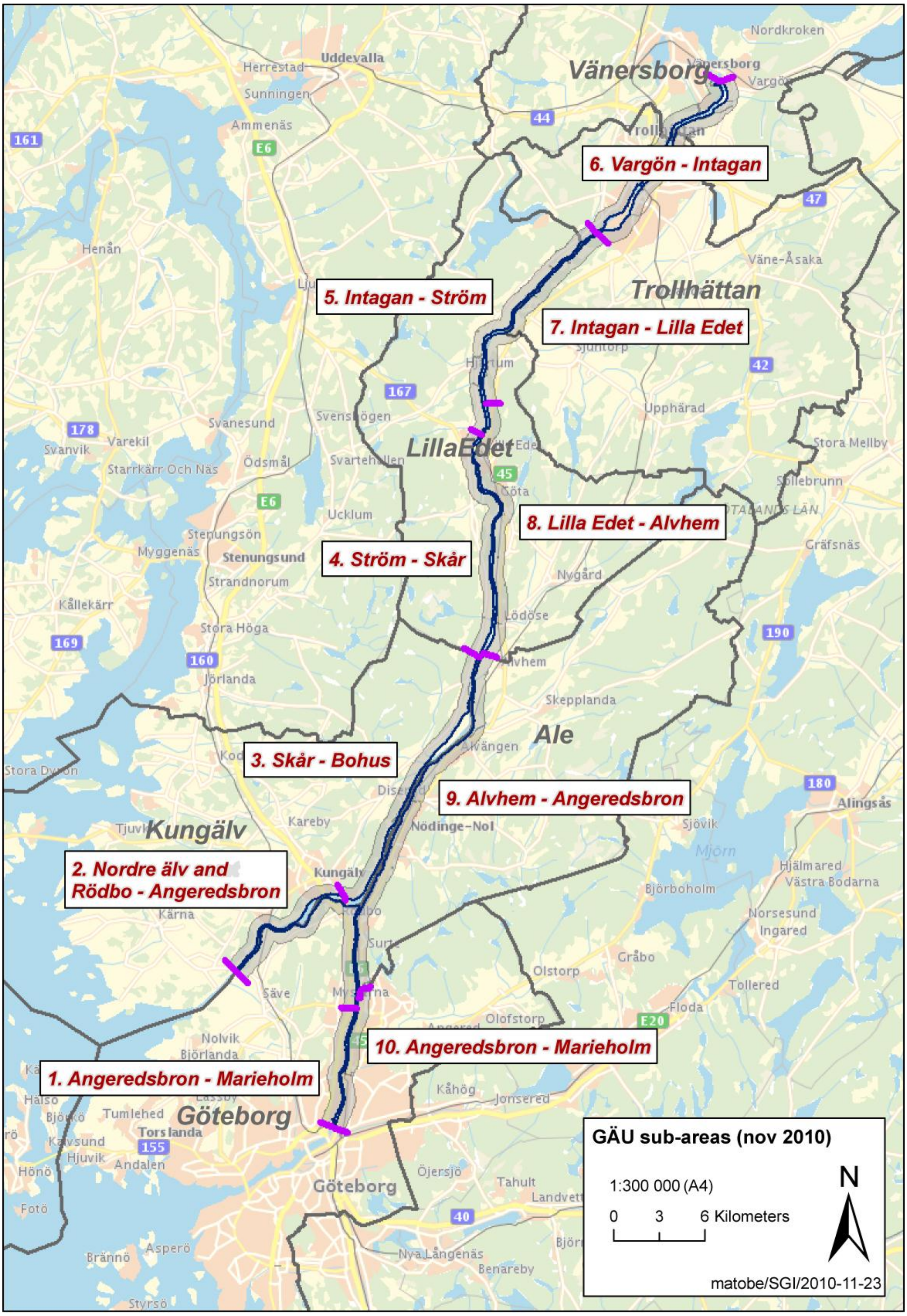


Figure 1-3
The geographic sub-areas along the Göta River valley.
Background map © SGI and Lantmäteriet

2 The Göta River valley - an overview

The Göta River and its valley constitute a central communications route in western Sweden and an important part of the region. The Göta River is one of Sweden's most water abundant river systems and its drainage basin is also the largest in the country. The river drains one-tenth of Sweden's total area and has a mean discharge of 550 m^3/s, which also makes it one of the largest river in Europe. The Göta River constitutes the only outlet from Lake Vänern, which is the largest lake in Sweden and the third largest in Europe. Due to the lake's immense volume, its turnover time is relatively long, 8-9 years and the flow time for water to pass through the Göta River is between 1.5 and 5 days, depending on the water level and drainage.

2.1 The Göta River valley - a district rich in nature and culture

The Göta River's valley and shores are of national interest, both in terms of their rich nature, which includes several ecologically sensitive areas, and the opportunities that they present for outdoor pursuits. The valley's coastal meadows exhibit great biodiversity. The Göta River is abundant in fish life and both the Göta and Nordre rivers are important migratory routes for several species, including salmon and sea trout. The Göta River valley also constitutes one of Sweden's oldest cultural districts, with a 1,000 year history surrounding Lödöse, which was Sweden's largest westerly port for a long time.

2.2 Residential areas and important social functions

The Göta River currently runs through six municipalities: Vänersborg, Trollhättan, Lilla Edet, Ale, Kungälv and Göteborg. Over 11,000 properties are registered within the investigation area near to the river, of which several are large industrial properties. There are over 600 "special properties" including school buildings, buildings used for healthcare and swimming or sports facilities. The Göta River stretches 93 km from Lake Vänern to its outlet in Göteborg, and its height of fall is 44 meters. Power stations and locks can be found at Vargön, Trollhättan and Lilla Edet, see Figure 2-1. There are also 20 or so registered sewage treatment plants that are located near the river, and the river is also an important fresh water resource and a source of water supply for approximately 700,000 people.

2.3 Communications route - shipping, road and rail

Shipping has long been conducted along the Göta River and approximately 2.4 million tonnes of goods are currently transported on the river each year, which means that around 1,600 cargo vessels traffic the Göta River every year. During the summer season, an additional 4,000 leisure boats pass through as well.

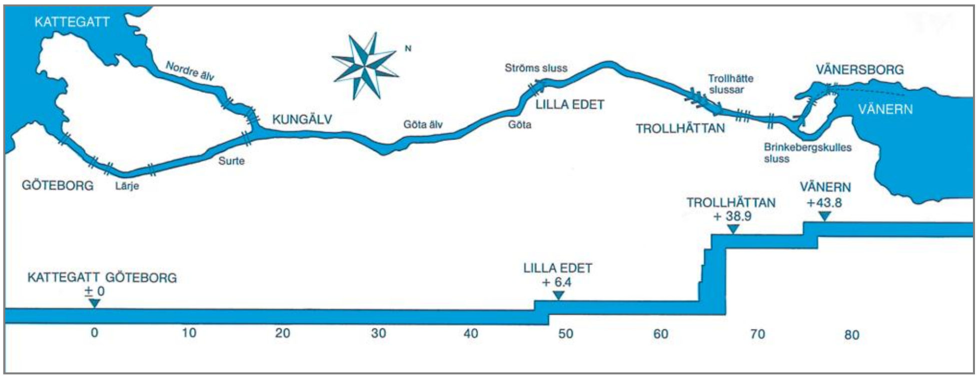


Figure 2-1
The Göta River – a waterway
Map image: The Swedish Maritime Administration

Within the Göta River valley, between Göteborg and Vänersborg, there are also land transportation routes that are of great significance for the development of the region. The road E6 runs between Göteborg and Kungälv on the river's western side and crosses the Nordre River within the area of investigation. On the eastern side, the road E45 and the Norway-Vänern line are directly adjacent to the river within the Göteborg-Alvhem stretch. The area of investigation also encompasses several passages over the river for both road and rail traffic. In addition to these main transport routes, there are a large number of smaller roads that were also encompassed by the investigation.

In 2004, the expansion of road and rail links along the Göta River was commenced in the project “BanaVäg i Väst”, which is planned to be completed during 2012. In Figure 2-2, the future road and rail sections can be seen. The railway is being expanded so that it has double tracks and the E45 is being expanded into a four lane motorway between Göteborg and Trollhättan. Between Göteborg and Älvängen, the road and railway run more or less parallel, near the river. In the northern section between Älvängen and Trollhättan, the railway bends further to the east. The number of passenger trains is expected to increase from the current daily level of 38 up to 168 per day in 2020, and goods trains are expected to increase from 26 to 44 per day.

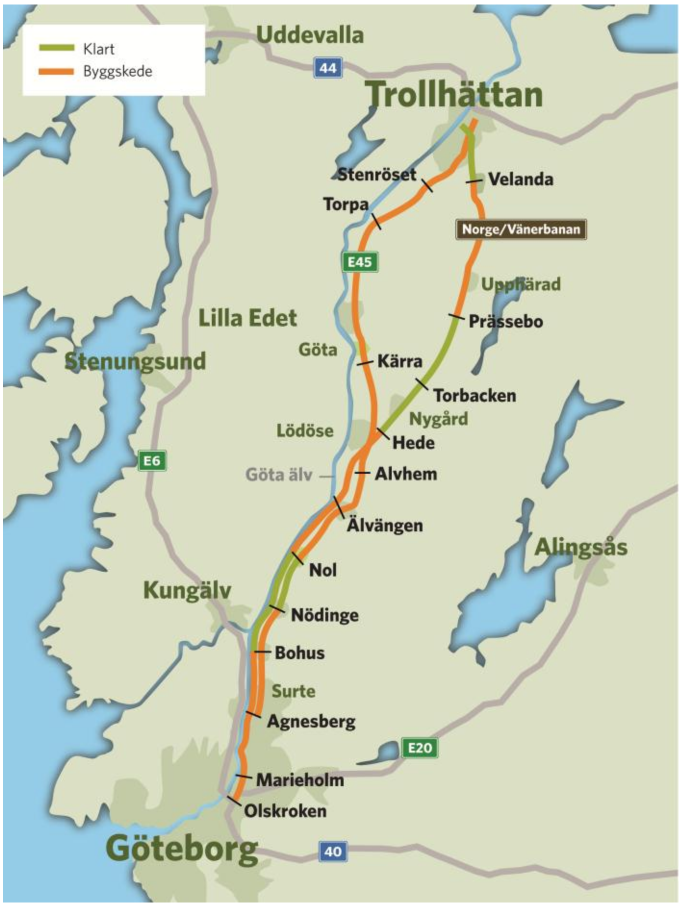


Figure 2-2
Ongoing and planned road and railway expansions in the Göta River valley.
Map image: The Swedish Transport Administration

2.4 Geological and geotechnical conditions

The Göta River flows through a valley which coincides to a large degree with a pronounced fault zone that stretches from the Vänern basin (*Sw*: Vänerbäckenet) to the other side of Göteborg. The bedrock consists primarily of gneiss and the formation of the valley is largely due to the system of cracks found within the bedrock. At Lilla Edet, the valley changes direction; north of Lilla Edet it runs northeast-southwest, whilst south of Lilla Edet it runs north-south.

Clay is the predominant soil type in the valley and it is extremely thick - over 100 meters in some places. The largest overall soil depths can be found at Dössebacka, where it is estimated that the bedrock is found at a depth of over 200 m. The soil depths are however extremely variable along the river and, north of Lilla Edet, the bedrock rises up in several places, sometimes as high up as the riverbed. The clayey soil has created special geotechnical conditions along the river valley and the countryside has, to a large degree, been formed by the effects of erosion and landslide processes.

The Göta River valley has the highest frequency of landslides in Sweden. SGI's landslide database contains records of over 60 landslides and soil movements along the Göta River, the majority of which have occurred in the stretch between Lilla Edet and Trollhättan. The majority of the larger landslides that have occurred in the Göta River valley have occurred in quick clay, a type of clay which, when disrupted, loses its shear strength, see below.

From a geotechnical point of view, the clay's shear strength, groundwater level and pore pressure (i.e. the pressure of the water in the soil) are important parameters for the calculation of the risk of landslides. Some of the most essential geotechnical terms are described below.

The clay's properties and groundwater conditions

The clay in the upper parts of the valley has an undrained shear strength classified as low to medium, and south of Lilla Edet it fluctuates between very low and medium. The clay is overconsolidated north of Lilla Edet and normally consolidated south of Lilla Edet, which implies that the clay north of Lilla Edet can withstand a certain external load without causing settlements. Seams of silt and sand occur frequently within the clay layers.

The fractured bedrock along the valley has caused large level differences, differences which amount to between 200 and 300 meters in some places. This has an effect on, among other things, the groundwater conditions. The groundwater level of the outermost layers of soils commonly found somewhere between the ground surface and a depth of around two meters. The infiltration of precipitation into these uppermost layers and the groundwater flow from them along underlying moraine, glaciofluvial deposits and coarser, embedded sediments in the often thick layers of clay, provide the preconditions for high groundwater pressure in the clay layers of adjacent valleys. When the pressure head in the groundwater in the underlying layers of coarser soil lies above the surface, artesian pressure prevails. High groundwater pressure and pore pressure reduces the clay's shear strength.

Highly sensitive clay/quick clay and landslide dispersion

One of the parameters used to characterise clay is its sensitivity, which is a measurement of how sensitive the clay is to disturbance. If a clay is classified as highly sensitive, this means that it loses its shear strenght when disturbed (i.e. by a landslide) and becomes very soft. In extreme cases, disturbance can lead to the clay becoming a fluid mass with no residual structure and solidity: in such cases it is classified as quick clay. An initial landslide in quick clay implies that the resisting forces in the slope behind the landslide are reduced, thereby triggering further landslides. In this way, a landslide in quick clay can gradually spread backwards and affect large areas.

Quick clay therefore entails a risk that smaller, local landslides can spread and become much more extensive. Such an incident means that secondary consequences can occur, in addition to losses of and damage to land. Examples of secondary effects that can occur are the disturbance of shipping, the damming of the Göta River (or its tributaries) and flood waves of varying magnitude, depending on the volume of the landslide's mass.

To assess the dispersion of clay landslides, a method is used whereby the backward extension of the landslide depends on the height of the slope and the clay sensitivity within the soil volume influenced by the initial landslide. The majority of known large landslides in the Göta River valley have occurred in highly sensitive clay, and in most cases, in quick clay. Landslides in quick clay can be extremely extensive and the incidents themselves are sudden and dramatic. The landslide that affected Surte in 1950 lasted for 2-3 minutes and, during that time, the clay masses slid away and moved houses within the landslide area 50-150 meters down towards the Göta River, see Figure 2-3. The landslide debris also blocked the river and impeded shipping.

Figure 2-3
The Surte landslide, 1950. Photograph: SGI

Another example from the Göta River valley is the Göta landslide of 1957, where a 130 meter long crack in the ground was first discovered, about three hours prior to the landslide that rapidly expanded along the river and inland. In a few minutes, the landslide expanded to encompass a stretch of the river approximately 1.5 km long, and areas approximately 200-300 meters inland from the river shore. Shipping in the Göta River was suspended for a month.

Within the scope of the investigation, particular attention has been paid to identifying and mapping the presence of quick clay. Quick clay and highly sensitive clay occurs along the entire river, but its presence is greatest north of Lilla Edet. South of that area, the clay is primarily of medium sensitivity, although quick clay does occur locally.

2.5 Topographical conditions

The valley is characterised by large level differences where surrounding mountain peaks often rise more than one hundred meters over the valley's ground level. Large soil depths, over 100 metres in places, are commonly found in the stretch between Lilla Edet and Göteborg and these have been formed in a valley that is deep and sharply curbed. In the northern part of the river, steep, high riverbanks have been formed, whilst in the southern part, there are steep underwater slopes surrounded by flat flooded areas.

During the last ice age, the whole of Scandinavia was covered by ice and the weight of these glaciers pressed down the Scandinavia bedrock. After the ice age, when the heavy burden of the ice was relieved, the areas of clay rose out of the sea. This is a process which is still ongoing and the uplift in the Göta River valley is currently 1-3 mm per year.

Changes in slope geometry due to erosion

The inclination of slopes above and below the water level is decisive for the stability of the slope. On land, the inclination is primarily affected by the run off of precipitation and land use. Under water it is primarily erosion that alters the inclination of the slopes.

Erosion is a continuous process and it is therefore necessary to take long-term changes into consideration. A continual change to the river's bottom levels has been observed, where both erosion and sedimentation occur. The underwater slopes of the river's canyons are gradually undermined by erosion, causing the occurrence of underwater landslides which develop further towards dry land. Areas where the river bottom is susceptible to erosion can be found in several places along the river, both near residential areas and where roads and the railway run relatively close to the river. There is erosion protection along large sections of the river and this counteracts erosion of the shore, but there is often no protection for underwater slopes. Damage to erosion protection has been noted in several places, especially in the southern parts of the area of investigation.

Erosion from waves and flowing water has formed much of the river's landscape that is visible today. Erosion affects the topography of the slopes and, in order to map the stability conditions and risks of landslides in the river valley, knowledge of erosion conditions is an important prerequisite. Within the investigation, measurements and calculations have therefore been conducted, in order to get an idea of the scope of the erosion in the current climate and what might be expected with increased flows in the future.

2.6 The Göta River valley in digital form

Göta River "viewer"

As part of the Göta River investigation, a large amount of external data has been collected and utilised, for example, geological conditions, property values, population statistics, infrastructure and the occurrence of risk objects. Furthermore, whilst the investigation has been in progress, a large amount of new data and results have been produced. In order to handle the large amount of data, a geographic information system (GIS) was used. A GIS platform was established together with a number of web-based GIS applications so that the collected and processed data could be easily handled.

The single most important GIS application is the so called "Viewer - Göta River". It contains almost one hundred layers, and hundreds of thousands of geographic objects. Examples of usable and easily accessible presentations in the viewer are the description of geotechnical field investigations in plan format, updated terrain models, geological maps, landslide scars along the river, etc. Figures 2-4 and 2-5 show examples of some of the presentations of the various data in the Viewer - Göta River.

During the investigation period, the viewer has been an extremely valuable tool for data analysis. Furthermore, the compilation of editable GIS applications has been used for the managing of the investigation results such as in descriptions of calculated slope stability, the existence of areas containing quick clay and the digitalised surface representation of analysed landslide risks.

Figure 2-4
Examples from Viewer - Göta River. Illustration of the property map, showing investigation sections, bore holes and contour lines. Background map © SGI, Lantmäteriet.

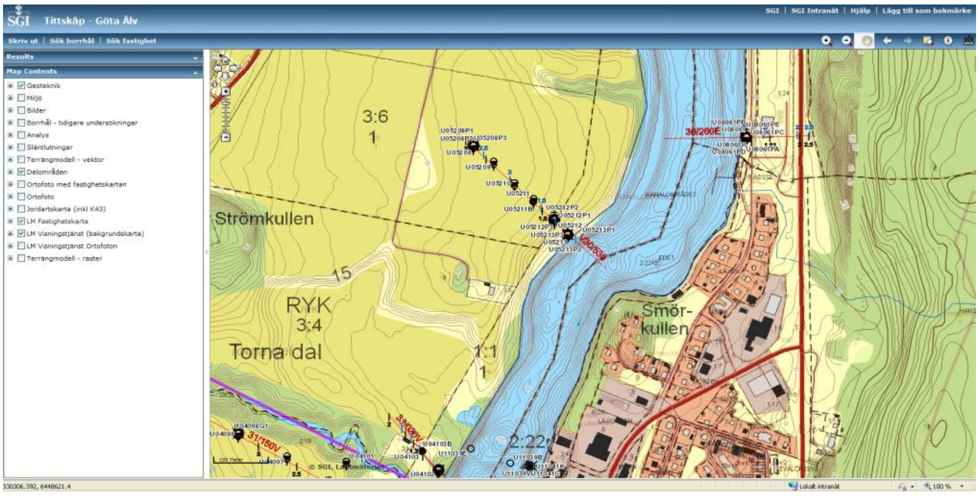
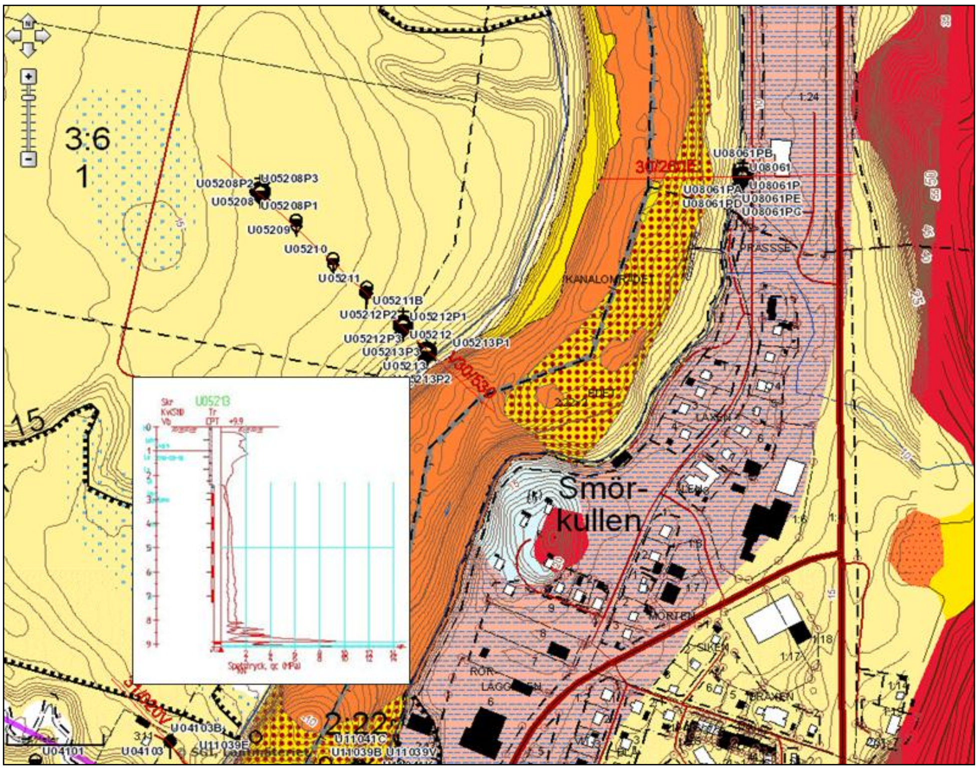
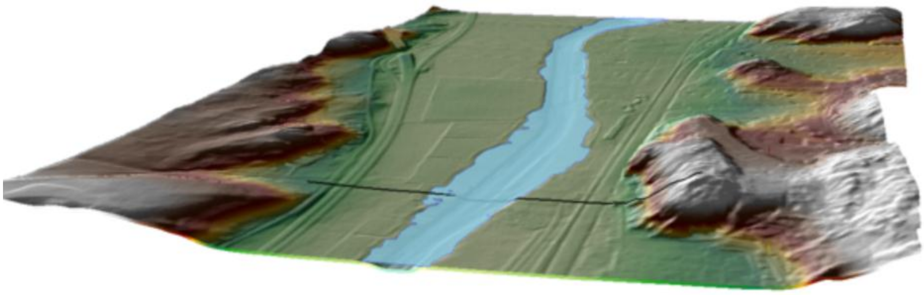


Figure 2-5
Presentation of the soil type map, including the geology of the soil types in the river, contours with an equidistance of one metre, investigation sections, as well as bore holes and probing diagrams (diagrams from GeoSuite). Background map © SGI, Lantmäteriet.



Terrain model

All landslide analyses should be based on a correct model of the terrain and, and for the Göta River, also the bathymetry of the river. Within the Göta River investigation, a digital terrain model has been established for the whole area of investigation, based on previously conducted laser scanning on land supplemented with multibeam echo sounding in the river. The terrain model has formed the basis for, among other things, the calculation of erosion and for stability calculations in specific sections. Figure 2-6 shows illustrations from the digital terrain model.



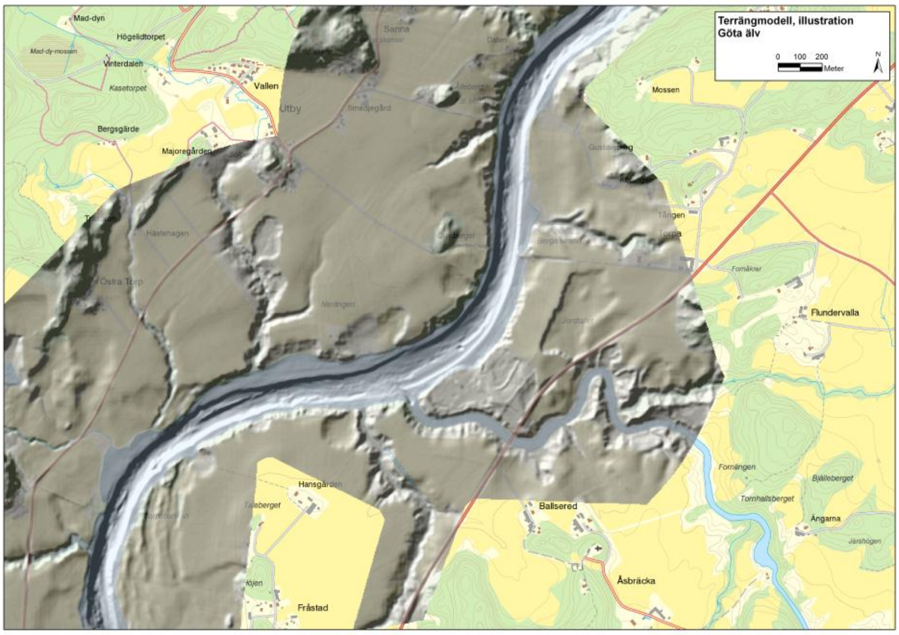


Figure 2-6
Illustration of the terrain model Göta River in 3D (above) and in plan format.

3 Climate changes

3.1 Temperature and precipitation in the climate of the future

Based on 16 different climate scenarios regarding future emissions of greenhouse gases, an analysis has been conducted of the manner in which the climate within the Göta River valley is expected to develop. Current and future hydrological and meteorological conditions are described, based on regional scenarios, and are included in the Göta River investigation's Interim report 27.

Figure 3-1 shows the estimated development of the mean annual temperature in the Göta River valley. As can be seen from the diagram, the mean annual temperature is expected to rise by 4-5°C by the turn of the century, compared with current conditions. The increase is expected to be greatest during the winter and least during the summer.

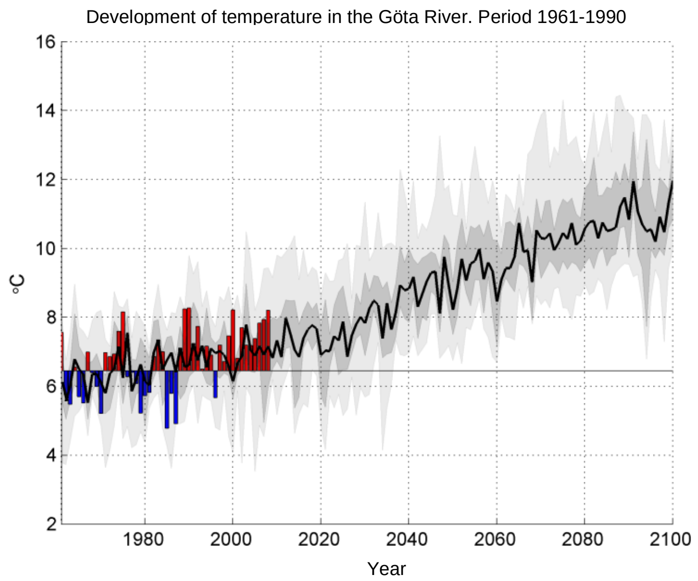


Figure 3-1
The estimated future development of temperature in the Göta River valley for the whole year, and observations for the same area (blue and red columns). The various shadings refer, from the top down, to: the maximum value, 75 % percentile, the median value (black line), 25 % percentile and the minimum value of the annual mean temperature, taken from all climate estimations. The mean value for the reference period's mean value (1961-1990) is shown with a horizontal line. (As per Bergström et al., Göta River investigation Interim report 27)

As can be seen from Figure 3-2, a gradual increase in the mean annual precipitation can be expected in the Göta River valley over the next 90 years with 20-30 % higher precipitation by the turn of the century, compared with current conditions (reference period 1961-1990). Precipitation increases most during the winter, but results vary greatly. It should be noted that the climate estimations indicate that the mean annual temperature will increase by 4-5 C during the same time period, which means that evaporation will also increase.

In the future, precipitation in the Göta River valley's drainage basin is expected to increase during the winter and to decrease during the summer, whilst it will remain largely un-changed during the spring and autumn.

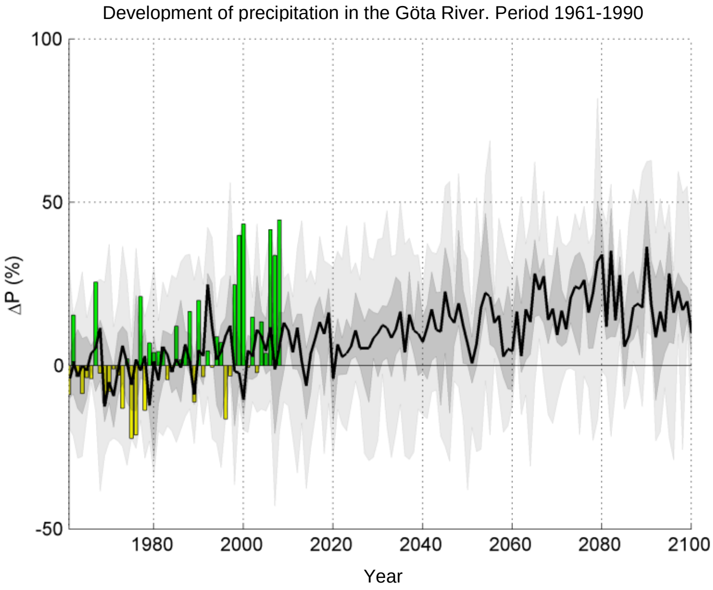


Figure 3-2
The estimated future development of precipitation in the Göta River valley for the whole year. The diagram also includes observations relating to the same area (yellow and green columns). The various shadings refer, from the top down, to: the maximum value, 75 % percentile, the median value (black line), 25 % percentile and the minimum value of the annual precipitation, taken from all climate estimations. (As per Bergström et al., Göta River investigation Interim report 27)

With regard to extreme climatic incidents in the future, there are large uncertainties in the assessments, but extreme daily precipitation is assessed to increase by 10 % up until the middle of the century and by 20 % up until the year 2100 for rain, with a return period of 100 years.

3.2 Changing flow levels in the Göta River

The future flow in the Göta River depends on the inflow to Lake Vänern. The expected climate changes give that the inflow may increase during the winter and autumn and decrease during the summer. Figure 3-3 shows that the climate changes will also lead to a different annual cycle, with respect to future inflow. This also implies that the flows in the Göta River will change in the future, so that higher flow levels will occur for longer periods. The flows that will be drawn off will ultimately depend on the drainage strategies adopted.

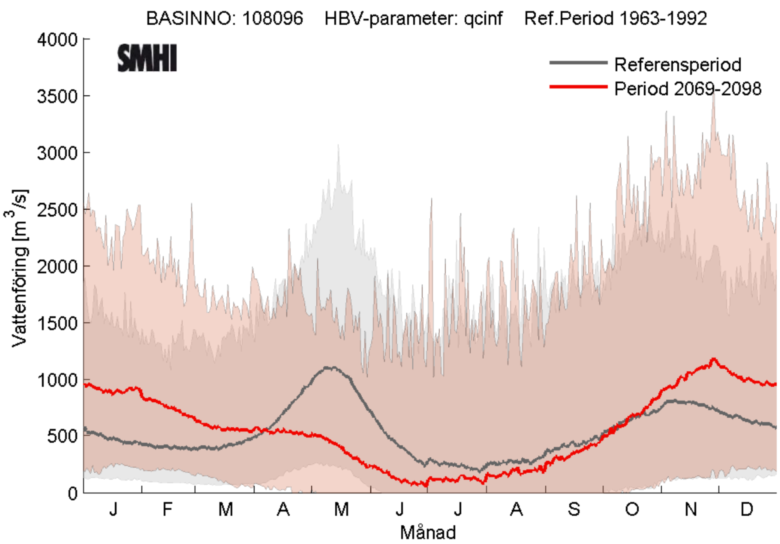


Figure 3-3
The changing annual cycle for inflow to Lake Vänern for the period 2069-2098, in relation to the 1963-1992 reference period. The grey shaded area comprises the reference period's range of variation (the 75 % percentiles of the maximum values, and the 25 % percentiles of the minimum values, respectively) and the pink area refers to the equivalent climate scenarios. The continuous lines represent the respective mean values. (As per Bergström et al., Göta River investigation Interim report 27)

Based on the changed inflow levels, the drainage estimations have been calculated largely in accordance with the drainage strategy from Lake Vänern that has been applied since the autumn of 2008. The estimations clearly show that high and low levels of drainage from Lake Vänern will become more frequent, if the climate develop as is described in the future scenarios.

3.3 Sea levels today and in the climate of the future

The opinions found within scientific research vary considerably with regard to how sea levels are expected to change. Furthermore, there are large regional differences. The assessment made in the climate analysis is that global sea levels will rise by approximately 0.3 m up until the year 2050, and by approximately 1.0 m up until 2100, calculated from the 1990 reference year. For Göteborg, with a compensation made for land uplift, this means a net development of the sea level in line with the diagram in Figure 3-4.

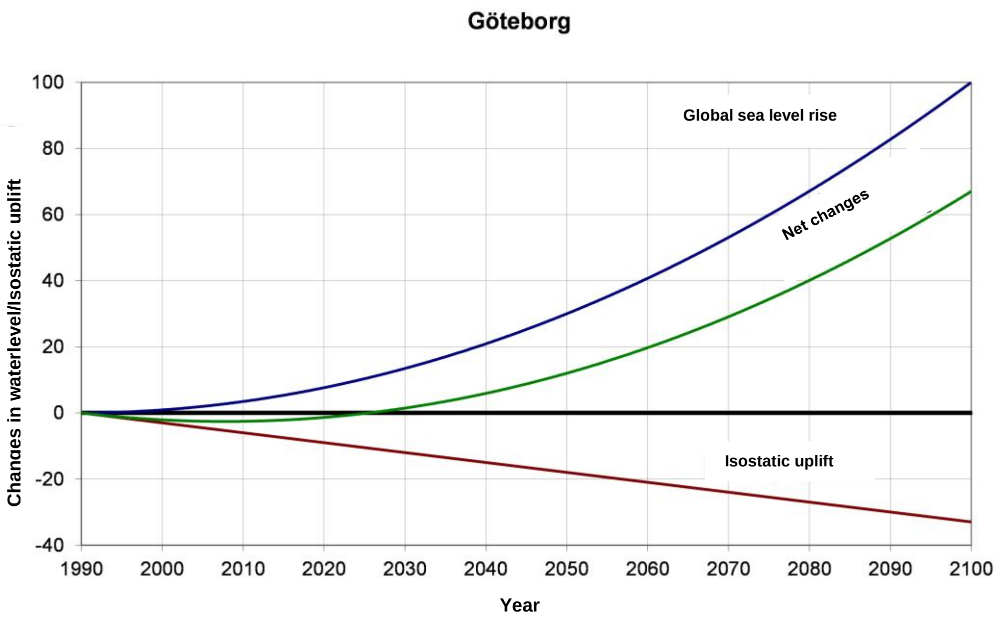


Figure 3-4 *Change in the sea level at Göteborg up until the year 2100 in the event of a global sea level increase of 1.3 m by 2050 and an increase of 1.0 m by 2100. (As per Bergström et al., Göta River investigation Interim report 27)*

As far as short-term extreme water levels are concerned, these are often linked to storms. Existing regional climate scenarios for Sweden give no unequivocal picture of how these will develop. As far as the future climate in the Göteborg region is concerned, there is currently no data on which to base recommendations regarding the considerations that should be made in respect to changed levels of storm intensity or storm frequency and the subsequent high water levels that would result from such.

4 The methodology used for landslide analysis in the Göta River investigation

The most important result from the Göta River investigation is the description given of the area's landslide risks, both current conditions and those resulting from a change in the climate. This chapter provides a description of important concepts and the methodology employed.

4.1 What is landslide risk?

The term "risk" can be defined as the answer to a combination of three questions:

- **What could happen?** Landslides can be caused both by natural processes (precipitation, erosion, etc.) and by human elements (overloading, excavation, etc.). A landslide has a geographical limitation and develops rapidly. One important issue has been to determine how wide landslides could spread, at different locations along the river.

- **How likely is it that it will happen?** The probability of a landslide occurring has been estimated based on mapped and measured geotechnical variables and the variation these variables exhibit. The probability has been estimated in a large number of sections that are representative of the areas that surround them.

- **What would the consequences be?** The consequences of a landslide have been estimated as the direct costs to residential areas, including human lives, and the cost to critical social functions that are affected by the landslide, as well as indirect costs such as, for example, the diversion of traffic from a particular road, or a fall in industrial production levels.

Landslide risk is defined as a combination of the probability of a landslide and the consequences of such an incident. Three levels of risk are described: low, medium and high.

4.2 Mapping the geotechnical slope stability

Safety against landslides, which is also known as slope stability, is often expressed as the relationship between a slope's resisting forces and the driving forces. This relationship is known as a "safety factor". The resisting force consists primarily of the soil's shear strength but also stabilising forces from, for example, the weight of water in a water course, or resisting forces provided in the form of soil and rock filling in the lower part of the slope. The driving forces arise as a result of the soil's own weight and the pressure on the ground resulting from buildings, the storage of materials and other loads. A common method for increasing stability is to remove soil masses above the crest of the slope, in order to reduce the impelling load, and to fill the lower part of the slope with these masses in order to increase the resisting force. The topography of the terrain, for example, the inclination of the slope, is a central parameter in terms of the slope's stability.

In order to obtain as good a description as possible of the actual situation, the traditional calculation of safety factors has been supplemented with an assessment of the probability for landslides, with due consideration is paid to the uncertainty of the parameters involved. Stability is analysed with the aid of parameters which provide a variation that describes their uncertainty. The variation is determined in each individual case using experience gleaned from similar areas and with statistics taken from investigations and measurements. Several parameters change over time and as a result of climate change, which means that calculations have to be performed both for present and future conditions.

The landslide probability has been divided up into five categories, P1-P5. The boundaries between the various probability categories have been set based on the European and Swedish building standards generally used in the construction of buildings. The categories used in the Göta River investigation have been selected so that probability class P5 implies the worst class that can be accepted for temporary constructions, whilst probability class P1 implies a standard of stability that is better than that required for regular buildings.

4.3 Assessment of the consequences of landslides

The methodology employed for the assessment of consequences comprises a number of steps, including:

- identifying the object or objects that might be affected within a certain, demarcated area
- assessing the extent to which a landslide might affect this/these object(s)
- making a monetary assessment (costs) of residential areas, human lives, roads and railways, energy and electricity systems, water and sewage systems, environmentally harmful operations and polluted areas, and for industry
- assessing the effect on the natural environment and cultural heritage

The consequences of a landslide are described principally as those direct costs for mankind, ground areas, residential developments, infrastructure, etc. that result from the landslide. For roads and railways, the cost for traffic redirection is included, as is the fall in production levels suffered by industry. The time aspect is extremely important, i.e., the time it takes a business to restore or rebuild its operations. All consequences have been allocated a specific economic value. The costs for secondary landslides that affect, among other things, shipping, have been included in the calculation of consequences.

Methods and information with which to conduct a monetary assessment are not available for some conditions. Within the investigation, it has not been deemed possible, within the scope of the valuation of consequences, to include monetary values for natural or cultural values.

The consequences of landslides are presented as consequence categories C1-C5. The boundaries between the various consequence categories have been determined based on previously conducted mappings of landslide risks and experience from landslides that have occurred previously.

Landslides in the Göta River valley can affect many people and important social functions. An exhaustive description, and, above all else, an economic valuation of all the consequences, has not been possible within the scope of the Göta River investigation. For many people, landslides lead to suffering, grief or discomfort, but this cannot be easily assessed in monetary terms. The way that the risks are changing, parallel to the way in which society is developing, and the heightened consequences of landslides that may result from new, riverside developments have been considered a "genuine uncertainty" and have not been specifically quantified within the investigation.

4.4 Compilation of landslide risks

Landslide risk is defined as a combination of the probability of a landslide and the consequences of such an incident. Each individual area within the investigation's boundaries has been allocated a probability class (P-class) from *Negligible risk of landslides* (P1) to *Obvious risk of landslides* (P5), and a consequence class (C-class) from *Slight consequences* (C1) to *Catastrophic consequences* (C5). Each individual area can therefore be described with a number couple ”P/C” which represents the probability/consequence combination. Visualisation of this combination of probabilities and consequences can be illustrated in a matrix of the various combinations, see Figure 4-1. The landslide risk is indicated through three risk levels: low, medium and high, with the corresponding colors: yellow, orange and red.

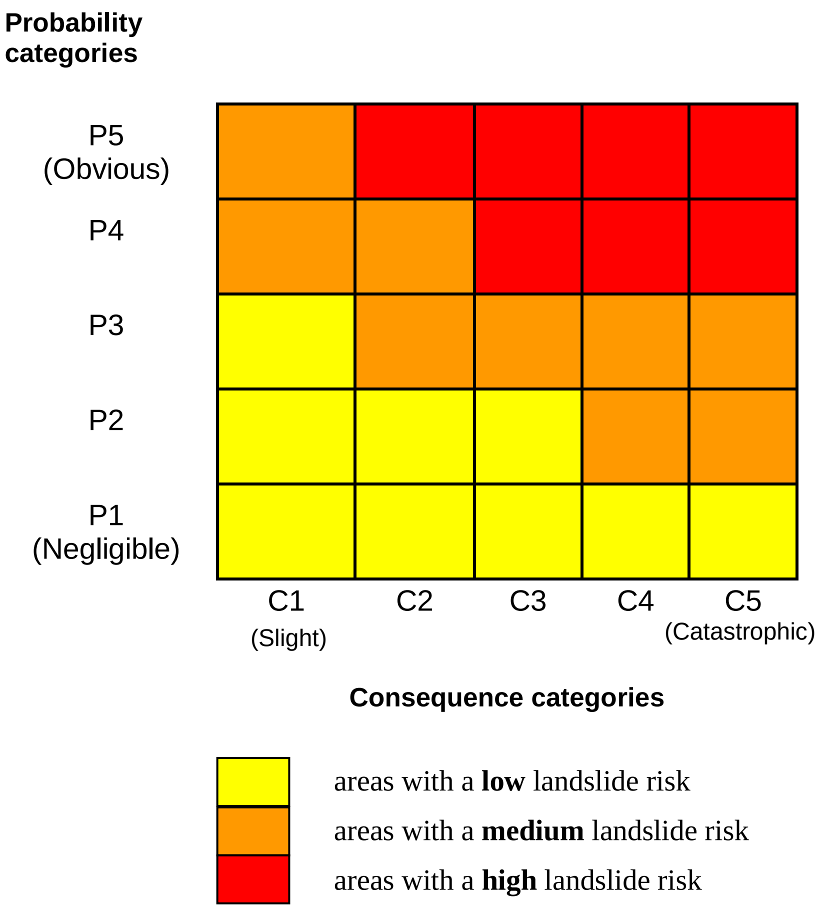


Figure 4-1
Matrix with landslide risk levels based on the probability of a landslide and its consequences

4.5 Descriptions of landslide risks on maps

The landslide risk for various areas along the Göta River are described in the Göta River investigation, Final report, Part 3 - Maps. Three different risk levels are specified (low, medium and high) on 1:10,000 scale maps that cover the entire investigation area. The risk levels are illustrated in yellow, orange and red, respectively.

The maps also describe the probability of a landslide (categories P1-P5) and the potential consequences (categories C1-C5) in the form of number couples, P/C. The number couples have been placed at representative locations within the respective risk areas. The maps shows combinations of the probability of a landslide and the primary consequences of such an incident, i.e., the loss of human life and damage to existing properties and facilities on land.

Furthermore, the areas where initial landslides are assessed as being able to spread quickly as a result of subsequent "retrogressive slides", so called "quick clay landslides" are also presented. In order to take the possible secondary effects of landslides in the Göta River valley into consideration, the areas nearest the river with highly sensitive clay/quick clay and a high probability of landslides (probability class P4 or P5) have been marked with a dotted line on the risk maps. This indicates that there is an obvious possibility of a larger landslide in this area, and consequently, a greater risk (more serious consequences).

Finally, the maps indicate the effects that can be expected as a result of climate change. Climatic impact has been reckoned as something that has an effect on the probability of a landslide, and it has been classified as having either a minor, moderate or large impact.

5 Landslide risks in the Göta River valley

5.1 The challenges of a changing climate

High water flows in the river affect residential areas and infrastructure, partly through direct stress on constructions in the water and partly through erosion and the subsequent deterioration of adjacent slopes. Increased flow means increased erosion of the whole cross section, including underwater slopes, and it is primarily this erosion and the removal of the shore edge that has formed the basis of the stability calculations for the climate of the future. It is along the stretches with the highest levels of erosion that the probability of landslides will change the most. Erosion is greater in the southern part of the river and therefore the risk of landslides also increases the most in this part. This occurs, however, largely within areas that currently have a relatively low risk of landslides. In the northern part of the river, north of Lilla Edet, there is less erosion but, on the other hand, erosion occurs within areas that already have a high landslide risk and where even small changes can trigger a landslide.

Increased flow is a consequence of increased precipitation in the climate of the future, something that also affects the groundwater level and the pore pressure in the soil. The investigation has shown however that the relatively limited change in the maximum groundwater levels and the pore pressure in the slopes that can be expected in the future, taking the climate scenarios into consideration, normally have a limited effect on stability conditions.

5.2 Residential areas and infrastructure

The consequences of landslides affect many values along the Göta River, including residential areas and important social functions such as the transport infrastructure, drinking water resources and the supply of electricity. The valley, with its coastal meadows, constitutes an area of national interest, due to its rich nature and the opportunities that it presents for outdoor pursuits. Sites of cultural interest and historic buildings can be found, along with modern residential areas, infrastructure and industries. Areas of polluted land and sediment can also be found within the region. Environmentally harmful activities also take place at many locations along the entire river.

The economic value of potential damage caused by landslides calculated using the investigation methodology amounts to SEK 144 billion, as a total for the whole of the mapped area. To this can be added a long list of other consequences for the local community that can be greatly significant, the costs of which have not been specifically calculated in the investigation. A sensitivity analysis of the variation in the various cost items has been conducted and this shows, among other things, that restoration time following a landslide has a large impact on costs, when roads and other infrastructure are concerned. The consequences within all areas with a high landslide risk (red areas) are valued, given current conditions, at just over SEK 7 billion, and for areas with low stability and a landslide probability class of S4 or S5 (red, and parts of the orange-colored areas) the total cost of the consequences amounts to approximately SEK 10 billion. These costs do not include any secondary effects caused by large landslides. In addition to the estimated costs attributed to the landslide, large landslides can also lead to other consequences for the local community whose costs have not been estimated, but which can be very substantial. The costs of consequences are distributed over the whole area of investigation, but the highest costs are, to a large extent, linked to densely populated and developed areas, even if high costs for consequences can also be found in the less densely populated and less exploited sections along the river.

5.3 Shipping

Shipping is directly affected by landslides into the river. Even smaller landslides can entail a suspension of or disruption to shipping traffic. Dredging is sometimes required to restore the depth of the shipping channel, following a landslide. Dredging is also required to restore the depth of the channel as a result of the aggradation caused by sedimentation. Dredging is currently conducted primarily in the southern sections of the Göta River, between Göteborg harbour and the outlet of the stream Lärjeån.

Shipping affects erosion, but the investigation has shown that, as far as the transportation of eroded material along the river is concerned, the contribution of shipping is probably limited. As far as the erosion of the slopes is concerned however, the contribution of shipping is considerably greater and the passage of shipping plays an important role in the erosion of shore edges. The speed of the shipping is of great significance here.

5.4 Environmental impact

There are around 50 environmentally harmful businesses registered within the Göta River valley. Along the Göta River there are eight Seveso-classified facilities that handle environmentally harmful agents in close proximity to the river, and another ten or so areas where the land has been identified as being polluted. Increased erosion means increased transportation of particles and increased turbidity (cloudiness). A landslide upstream of an effluent intake adjacent to the river can lead to the intake needing to be shut off due to cloudiness and possibly also due to environmentally harmful agents having reached the river. Within the investigation, the total extra costs associated with decontamination of polluted land in the event of a landslide are assessed as amounting up to SEK 20 million per hectare, depending on the scale of the landslide.

5.5 Landslide risk zones today and in the climate of the future

The mapping shows that there are many areas of high risk along the Göta River and that the risks are higher in a changed climate. The change in climate means that the risk of landslides will change for several areas. A calculation of the impact of climate change in 200 geotechnical sections resulted in 25 % of them receiving a higher risk level in 2100 than they currently have. If no measures are taken, the risks in areas with the greatest risk of landslides (the red-colored areas on the landslide risk maps) are expected to increase by 10 % in relation to their current level, up until the year 2100.

The major areas with high landslide risks can be found in the northern part of the river. The stretch from Trollhättan to Ödegärdet, south of Lilla Edet, constitutes the largest continuous area with high landslide risk. The area is characterised by high, steep slopes and deep, steep ravines. The area contains numerous traces of previous landslides. Around half of the approximately 20 km long stretch is categorised as having the highest probability of landslides (P5) and, in addition to this, there are many areas with the next highest probability class (P4), combined with the consequence class C3-C5. Within this section there are long stretches with highly sensitive clay, primarily on the river's western side, but also to the east. Large areas have been marked as having a heightened risk of secondary effects, including those resulting from the large impact on the river in the event of extensive landslides. The climatic impact is mainly low to moderate, but when this impact occurs within areas which are already classified as having a high landslide probability, this can have serious consequences.

Erosion is already extensive South of Lilla Edet, and is furthermore increasing appreciably with a changing climate, which means a greater climatic impact on the risk of landslides. This is occurring, however, along a stretch which at present mainly has a low risk of landslides, but this still means that the level of risk can increase within certain sections. Along the Göta River, south of Bohus, there are several narrow areas with moderate risks and, in certain narrow sections closest to the river, even high risks. Climatic impact is great within this section.

Within the risk zones that are marked on the landslide risk maps, there are several especially exposed sections along the Göta River; please note that the list below is not comprehensive. The areas with high risks can be found at many locations alongside the river and these risks must be managed for every single location.

Gäddebacke, Vänersborg municipality – On the eastern side of the river there is an area with a probability class of P4 and a high landslide risk. Within this area there is a levee that is to protect the area behind it from flooding. The levee is classified as a high consequence dam (consequence class 1A) in accordance with RIDAS-Kraft Corporate guidelines for dam safety issued by Swedish Energy.

Åkerström, Trollhättan municipality – An area with an integrated residential area and the highest landslide risk probability class (P5). The area currently has a high landslide risk.

The densely populated area of Lilla Edet – Within the densely populated Lilla Edet area there are several areas with a high landslide risk on both sides of the river. Within several parts of the area, the probability class is P5 or P4 closest to the river, and the presence of quick clay can cause secondary effects. The high landslide risk is most widespread on the western side of the river, but it also applies to the eastern side, within several demarcated areas.

The old paper mill, Lilla Edet municipality – A large area where quick clay is present and which has the highest landslide risk probability class (P5). The area that has been marked with a high landslide risk is located just north of the site of the Göta landslide of 1957.

The Älvängen industrial area, Ale municipality – Within the existing industrial area, there are landslide risks classified with probabilities of P4 and P5, closest to the river. Stability problems have been noticed in this area, in addition to areas of polluted land. The area has been marked as having a high landslide risk.

Kärra-Backa, Göteborg municipality – Steep underwater slopes cause low stability and areas with medium landslide risks have been identified along fairly long stretches of the Göta River, down towards Göteborg. Within this stretch there are also small areas close to the river with a high risk and these falls into the highest landslide probability class, P5.

The Nordre River's northern shoreline, Kungälv municipality – The landslide risk probability class P4 applies to the two areas closest to the river. The areas have been marked as having a high landslide risk.

6 Measures and costs

The investigation demonstrated that there are landslide risks along the Göta River, both from short-term and long-term perspectives. This means that measures must be taken, both to reduce the risks that exist under current conditions and to prevent the landslide risks presented by a changing climate.

The landslide risk areas described in the maps used in the investigation provide the data for the basis of decisions regarding measures to improve the stability of the river valley. The investigation has reduced the uncertainties regarding where the risks are located within the area of investigation, and through communication with the municipalities involved, several more detailed stability investigations have been initiated. The investigation represents a concrete source of information on which to base planning for increased flows and, consequently, climate adaptation in the Göta River valley.

Water levels in Lake Vänern and the flows within the Göta River are regulated by the applicable water legislation. The climate of the future will entail reduced inflow during the summer and increased inflow during the autumn and winter. Both high and low drainage levels will become more frequent. The future water management of Lake Vänern and the Göta River must be resolved through a balancing act that involves many interested parties. The geotechnical safety aspects are relevant primarily within the areas that already have a high risk level or a high landslide probability classification. There are however many identified areas where the risk of landslides will increase noticeably, from low risk to medium risk, and from medium risk to high risk, as a result of the climate changes that are expected within the next 100 years. However, from a shorter perspective, the climate's impact on landslide risks will be limited.

6.1 The need for stabilising measures

Landslide risks can be limited both through reducing the probability of a landslide and through mitigating their consequences. The latter, the mitigation of consequences, is linked to social planning and the development of society, and also to land use and the location of plant facilities and residential areas, as well as how existing structures are utilised and developed. These are important aspects that must form a central part of the risk management process in municipal and regional planning.

The probability of landslides can be reduced through the implementation of measures to improve stability. This involves both the improvement of existing stability conditions and ensuring that stability does not decrease in the future.

The need for measures to improve stability must be weighed up against the options available for reducing the risks in other ways, for example, by moving a business operation or by altering land use. This investigation has chosen to calculate the scope and costs for stability improvement measures so that stability is improved by at least 20 % within those areas where the probability of landslides is in the class P4 or P5. This involves stability improvement measures along approximately 60 km of the river - 35 km on the western side and 25 km on the eastern side.

6.2 Technical principle solutions and cost estimation

The need for stability improvement measures has been estimated and a rough assessment has been made of the costs of these measures. The assessments have been made based on an appraisal of all the risk levels for landslides along the river, erosion processes and areas that could possibly flood taking climate change into consideration. The assessment of the measures required has been conducted both for a scenario equivalent to the current situation and the current drainage through the river, and for a maximal future drainage corresponding to 1,500 m^3/s (during part of the year).

The need for **stability improvement measures** has been assessed, based on calculations of excavations at the slope crest and the flattening of slopes that is necessary along the river, see Figure 6-1. Other more costly methods may be necessary in certain cases, for evacuation purposes or due to environmental concerns. Along certain parts of the shore, where residences are located nearby or where the depth of the river channel is limited, solutions such as the moving of buildings or industrial facilities, pile driving or other measures may become relevant.

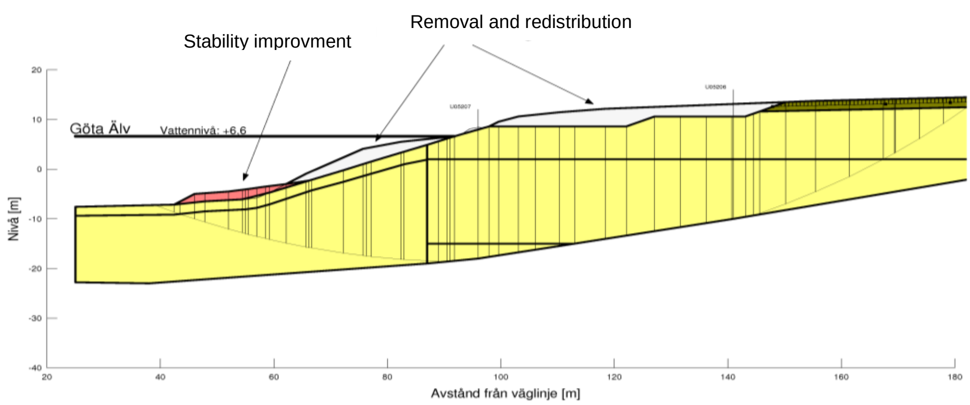


Figure 6-1
An example of the design of a section with improved stability due to the removal and redistribution of earth masses.

The need of more extensive **erosion protection** has been assessed and the costs for this have been estimated. It has been considered that there is a requirement for the existing erosion protection to be improved, as well as the construction of new protection. Increased flow and sediment transportation in the river is expected to lead to an increased requirement for dredging of the river's southern sections, primarily outside of the area of investigation. However, as long as dredging is not carried out to a greater depth, due to the possibility of the channel depth becoming altered in the future, it is not thought that this will affect stability along the Göta River, and consequently no cost assessment has been made within this investigation, with regard to dredging requirements.

The need for the **construction of levees,** where there is a risk that areas with existing housing or industrial land may be flooded, has been assessed for water levels in the river, based on current and projected future flow levels. An estimation of the costs for this has been made. The reason for attention being paid to levee construction within the investigation is that levees imply an increased load that can lead to a decrease of the slope stability. This needs to be investigated specifically, or in connection with a detailed investigation of different requirements associated with stability improvement measures or flooding risks.

The construction of levees in areas with lower consequences, for example, agricultural land in close proximity to the river, has not been taken into consideration within the investigation.

For the stability improvement measures to be implemented, **investigations** in the form of detailed stability investigations, the projection of measures and the establishment of construction documents are required, along with descriptions of the environmental consequences, permit applications, etc.

There is a requirement for the continuous **control/surveillance and maintenance** of the functioning of stability measures. The need for control and surveillance also extends to ongoing erosion processes. The need for measures is great, but it has been assessed that they can be kept at the estimated levels on the condition that the status of erosion protection, the erosion process and the flow levels are continuously monitored.

Table 6-1 shows the combined costs of the stability improvement measures, erosion protection, levees, investigations and the annual maintenance and surveillance of erosion protection and erosion processes. The cost is described both for the current situation and for a situation with a maximal discharge corresponding to 1,500 m^3/s. The combined costs are estimated at between SEK 4-5 billion, with discharge in accordance with water legislation (maximal discharge of 1,030 m^3/s) and at between SEK 5-6 billion for an increased discharge (maximal 1,500 m^3/s). Continuous surveillance and maintenance of erosion protection is estimated at an annual cost of SEK 6-7 million for current conditions and SEK 7-9 million in the climate of the future. Costs for the construction of levees adjacent to uninhabited low-lying areas or for the dredging of the river channels are not included.

Table 6-1
Total costs for the scenarios described

Measures	Current situation, max. dscharge 1,030 m^3/s (SEK million)	Future conditions, max. discharge 1,500 m^3/s (SEK million)
Stability improvement measures, erosion protection, levees	3,600 - 4,300	4,300 - 5,200
Investigations	400 - 450	450 - 500
Total (SEK million)	**4,000 - 4,750**	**4,750 - 5,700**
Annual maintenance	4 - 5	5.5 - 6.5
Annual surveillance	1.5 - 2	1.5 - 2
Total (SEK million/year)	**5.5 - 7**	**7 - 8.5**

7 Conclusions and proposals

The investigation has demonstrated that there are many areas within the Göta River valley that have a high landslide risk under the current conditions, and that these risks will increase as the climate changes. The change in the climate means that the risk of landslides will increase for about 25 % of the mapped areas up until the year 2100, compared with current risk levels. The extent of the areas in the highest risk class is expected to increase by about 10 %, up until the year 2100, at the same time as the probability of landslides will increase further within the already high-risk areas, if no measures are taken.

In the light of the large values that are to be found along the Göta River, the investigation concludes that it is necessary, and geotechnically possible, to take action so that drainage from the river can be increased, at the same time as the current risk of landslides is reduced. From a society perspective, the measures are considered as relevant in relation to the values that they are protecting. SGI's assessment is that the work in prioritised areas should be started immediately. The first stage involves clarifying the stability improvement measures that are necessary in the respective areas.

Based on the findings of the Göta River investigation, the following action plan for climate adaptation is proposed for the Göta River valley:

7.1 *Adapting the Göta River for increased levels of flow*

SGI proposes that the Göta River be adapted for increased flows, at the same time as current risk levels are reduced by stability measures in prioritised areas. The following measures should be incorporated into this adaptation work.

Measures to improve stability conditions

Measures to improve slope stability should be implemented in the areas nearest the river, where stability is calculated as being low, in areas that have a landslide risk probability classification of P4 or P5, which include all areas with high landslide risk as well as certain areas that have a medium landslide risk (the areas marked in red or orange on the landslide risk maps). Furthermore, SGI considers that measures must be taken to counteract the increasing of risks as a result of climate change. The measures should be instituted in order to reduce the probability of landslides given the current conditions and to prevent the risks arising from increased flow in the future.

A priority list for the measures should be established and the measures should be implemented in cooperation with the concerned authorities, property owners and other interested parties. SGI also believes that the relocation of certain operations should also be included as an option.

Geotechnical measures in the areas with low slope stability require sound planning and thorough preparation. Ground works in the areas with low stability and highly sensitive clay must be preceded by detailed investigation and design, in order to avoid landslides whilst the work is in progress.

Reinforce the river's erosion protection

The investigation indicates that there is a need to improve and reinforce existing erosion protection alongside the river's shores, above and below the water level. It is evident from the investigation that gradual erosion – which increases with increased flow – is the factor most critical to future landslides, along with the activities of mankind. The expansion of erosion protection should be preceded by investigations into the quality of the current protection and the need for new protection, especially for slopes under water and along the river's bottom. It is important to plan and design the protection against shore erosion and bottom erosion in order to counteract the increased landslide risks. This work is linked to the prerequisites for increased drainage in the river.

Furthermore, it is proposed that specific surveillance of erosion should be implemented, both in areas that currently have a high risk of landslides and in areas that are subject to large climatic impact. The inspection that SGI carries out in conjunction with Vattenfall and the Swedish Maritime Administration, and the surveillance that is currently performed along the river, should therefore be supplemented with surveillance of erosion and conditions at the bottom of the river.

A coherent process for increased slope stability and the development of society

The geotechnical stabilising work should be implemented within the framework of a coordinated planning process. Extensive stability improvement measures will require specific provisions in the local plans and Environmental Impact Statement of several of the areas. The permission of the Land and Environment Courts will probably be required for most of the activities. In order to handle this in a time and resource-efficient manner, it is proposed that the measures to improve stability are planned and prioritised comprehensively for the entire river.

There are residential areas and infrastructure located near the river in the area of investigation. The business operations are subjected to landslide risks but also to other geotechnically-related risks for damage, for example, as a result of settlements. Measures to improve slope stability can simultaneously create conditions for the development of new residential areas and infrastructure. SGI considers that the landslide risk situation along the river is such that the effects of climate change ought to be counteracted through a well-planned drainage strategy where both high and low flows are taken into consideration.

7.2 Delegation for climate adaptation in the Göta River valley

In order to implement sustainable climate adaptation in the Göta River valley, SGI proposes that the government appoints a delegation with representatives from various concerned interest groups, so that measures can be managed and implemented. The aim of the delegation is to coordinate, plan and implement measures that reduce the risk of landslides for existing residential areas and to prevent the risk of landslides for new developments and infrastructure, based on the current climate situation and that diagnosed for the future. The responsibilities of the various members can be clarified within the delegation, along with prerequisites for planning, the coordination of investments and the financing of the measures.

The delegation should consist of a permanent core of members, in order to provide continuity and a breadth of outlook. Furthermore, it is also suggested that the delegation should have political support or a clear proponent within the political system. The delegation should have specific government funding at its disposal, intended for the implementation of tangible adaptation measures in the Göta River valley. The work should be coordinated with the climate adaptation work that is in progress within the Lake Vänern region.

The establishment of a delegation for climate adaptation in the Göta River valley should be preceded by preparatory work where the compilation of the delegation, as well as its working areas, responsibilities and mandate are clarified. With the experience and the contact network that has been generated by the investigation, SGI has a sound basis for the performance of a specific government assignment such as this.

7.3 The further development of planning and decision-making data

The extensive information and results that have been compiled as a result of the Göta River investigation should be utilised for planning and construction within the river valley, as should the geographic information tools (GIS) that have been developed. The landslide risk maps that have been produced represent current conditions and the impact that changes in the climate can be expected to have. The GIS-based, entirely digital methodology that has been constructed for data storage, processing and reporting provides the preconditions for continuous updates and developments that are even more thorough and comprehensive. Simple and rational processes are required for updating, relating to the collection of data from municipalities and other concerned parties.

The investigation has shown that there is a need for additional knowledge on several issues connected with landslide risk analyses and surveillance, as well as increased efficiency in the geotechnical stabilising work and the investigatory work required in order to improve slope stability. Research and development are also required in order to improve knowledge of the effects of climate changes on geotechnical conditions. Examples of such initiatives are systems for the long-term measurement of groundwater levels and pore pressure in the river valley, as well as the development of more advanced models that describe erosion processes.

A model for climate adaptation work has been developed within the Göta River investigation, and the experience gleaned from this should be used for corresponding work in other parts of the country. The methodology that has been developed and the mapping implemented are also relevant for international application.

SGI considers that the Göta River investigation is a tangible step in the work to adapt society to a changed climate. One fundamental conclusion is that geotechnical adaptation for the climate of the future also has positive effects on the conditions that prevail today. SGI considers that the climate adaptation work must be integrated as an important part of current planning and land development processes.

Appendix

Göta River Investigation, GÄU – Interim Reports

1 **Erosion conditions in the Göta river, Sweden**
Bengt Rydell, Linda Blied, Håkan Persson, Wilhelm Rankka

2 **In-depth study on erosion in rivers**
Bengt Rydell, Håkan Persson, Linda Blied, Sofia Åström, Walter Gyllenram

3 **Göta river hydraulic model. Water and levels, currents and bed shear stresses**
Sofia Åström, Dan Eklund, Sture Lindahl

4 **Transport of suspended sediments in the Göta river, Sweden**
Gunnel Göransson, Håkan Persson, Karin Lundström

5 **Surficial geology survey by backscatter analysis of the Göta and Nordre river, Sweden**
Marin Miljöanalys AB

6 **Sea bed conditions in the Göta river, Sweden**
Fredrik Klingberg

7 **Evaluation of groundwater conditions in slopes along the Göta river – General guidelines**
Håkan Persson, Per-Evert Bengtsson, Karin Lundström, Petter Karlsson

8 **Sensitivity analysis for ground water level variations and estimation of maximum pore pressures in slopes along the Göta river – Example from a slope**
Håkan Persson

9 **Estimated change in maximal ground water levels in the Göta river valley due to climate change**
Linda Blied, Håkan Persson

10 **A study of the impact on pore pressures from precipitation and river level changes in three slopes along the Göta river**
Linda Blied

11 **Analysis of pore pressure measurements in the slopes at Äsperöd and Åkerström**
Thomas Rihm

12 **Methodology for inventory and assessment of consequences of landslides in the Göta river valley**
Yvonne Andersson-Sköld

13 **Consequences of landslides in the Göta river valley – Sensitivity analysis, classification and application of the methodology throughout the study area**
Yvonne Andersson-Sköld

14 **Consequences of landslides in the Göta river valley – The built environment**
Stefan Falemo

15 **Consequences of landslides in the Göta river valley – Identification, exposure, vulnerability and valuation of life**
Stefan Falemo

16 **Consequences of landslides in the Göta river valley – Shipping**
Ramona Bergman

17 **Consequences of landslides in the Göta river valley – Roads**
Ramona Bergman

18 **Consequences of landslides in the Göta river valley – Railroads**

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