Climate change induced river erosion as a trigger for landslide

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ABSTRACT
Most landslides are triggered by precipitation, river erosion, or human impact, or both. Regions experiencing an increase in precipitation from climate change may be at elevated risk for increased landslide frequency. The Swedish Geotechnical Institute is developing a methodology for landslide risk analysis and mapping along Swedish rivers and with the consideration of climate change effects. River geometry is dynamic and is under constant change, however most slope stability analyses are made under the assumption that the condition is static. No consideration is taken to future changes in slope geometry from river erosion. But, is it even possible to assess how river cross sections will change in future along with the effect of increased river flows due to the climate change? There are yet no models that can combine soil mechanics with hydrodynamic processes.
The Swedish Geotechnical Institute is developing a methodology to calculate possible future changes in river cross sections and with respect to climate change effects The approach is based on various measurements and analyses like bathymetric surveys, sediment characterization, hydrodynamic modelling of river flows, analysis of shoreline displacement with time by using aerial photos, and comparison between old and new cross sections. Erosive river flows are assessed and the duration of such flows in future (year 2100) is estimated based on existing climate analyses. Comprehensive calculation of river bed erosion is made in GIS, and is combined with bank erosion calculation in chosen cross sections. Calculation of slope stability and the probability of slope failure are then done for several cross sections, both for today´s geometry and for an expected geometry by year 2100. The approach was first developed in the landslide risk analysis for Göta Älv river, Sweden, and further developed and simplified for Norsälven River, Sweden. Currently, a landslide risk analysis for Säveån river has just been started.

Keywords: Bed erosion, bank erosion, slope failure, climate change

1 INTRODUCTION

When the water current is strong enough, particles will be detached and carried by the flowing water. There will be an exchange of particles on the river bed where some settles and other are detached and erosion occurs when it disappears more particles than what is settled. Sediment transport concerns both fine particles and coarser particles. Simplified, sediment transport is governed by bed slope, flow depth, flow velocities, particle size, and particle fall velocities (see for example Chanson, 2004). The forces that act on the particle are in general lift, drag, buoyancy and gravity. In addition, cohesion, biofilms, consolidation etc. affects. While gravity (and cohesion, biofilm and consolidation) is the stabilizing force, the others (lift, drag, buoyancy) are the destabilizing forces. Mobilization of particles occurs when the destabilizing forces are greater than the stabilizing forces. The threshold for mobilization is very difficult to determine with accuracy but many empirical observations have shown reasonably accurate and consistent responses (Chanson, 2004). Erosion in rivers has been studied by many to understand the processes of bed and bank erosion, sediment transport during peak flows, sediment fluxes etc. Most studies on fluvial erosion and sediment delivery concern individual flow peaks and are based on historical data (empiric based studies). However, there are yet no reliable models that combine geotechnical properties that act across a watercourse with the hydrodynamic processes that act along a watercourse, and in a long-time perspective. Some attempts have been done (Darby et al., 2007; Midgley et al., 2012; Rinaldi and Darby, 2008) but there is no general approach available. Darby et al. (2007) combined hydraulic erosion and limit equilibrium stability models to simulate mass wasting for cohesive river banks. They simulated erosion for single flow events and only for bank erosion, i.e. bed erosion was not included. Midgley et al. (2012) used a bank stability toe erosion model (USDR-ARS, 2015) to simulate bank erosion for a longer time period. Bed erosion not included. Both Midgley et al. (2012) and Darby et al. (2007) concluded that accurate data on pore water pressure is important and that sediment delivery from undercutting is difficult to manage in the calculations. Lévy et al. (2012) tried to identify the impact of long-term bank erosion for landslide from aerial photographs and laser measurements. They concluded that the method is time and cost effective but depends largely on the quality of available data.

Rinaldi and Darby (2008) concluded that conceptual models might be available but quantitative treatments that include interactions between fluvial erosion and mass failure processes are lacking.

This paper is the first to presents an approach to make prognosis of future river bed and bank erosion with respect to the effects of climate change. The study is part of a landslide risk analysis in a changing climate. The objectives are to *i*) make a prognosis of river bed erosion to year 2100 and with respect to increased river flows from climate change, *ii*) make a prognosis of river bank erosion in representative cross sections and with respect to increased river flows from climate change, and *iii*) to provide basis for forecasting the probability of landslides along the river stretch with respect to both river bed and river bank erosion to the year 2100.

2 METHOD

2.1 Study site description

The study site is the Norsälven River that runs from Lake Lower Fryken and debouches into Lake Vänern, Sweden. The river stretch is 28 km (ca 60 km shoreline) but is separated by two hydropower stations at 5,5 km and 11 km downstream the outflow from Lake Lower Fryken (Fig. 1). The survey area extends 600 m on each side of the river.

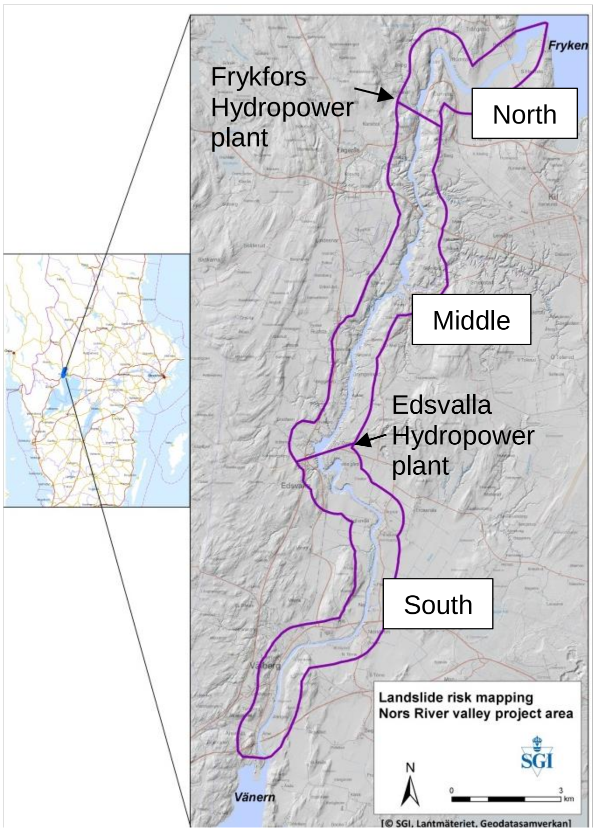

Figure 1. River Norsälven from Lake Lower Fryken to Lake Vänern. The figure displays the area in hill shaded topography and shows the investigated area as part of the Landside risk analysis. The stretch is divided into three parts separated by two hydropower plants. © SGI, Lantmäteriet, Geodatasamverkan.

The river is limited meandering and flows in a glacial sediment-filled valley that is characterized by severe gully formation and landslide scars. The sediment consists mainly of fine sediments that at some parts are underlain by coarser glacio-fluvial deposits. The high silt content in the fine sediment makes the soil vulnerable to erosion.

River mean flow is 51 m^3/s and the mean high water flow is 190 m^3/s. The highest flow

that has been registered between the years 1968-2013 is 393 m^3/s and occurred in May 1997 (open data source: http://vattenwebb.smhi.se/). The 100-year flow (Q_{100}) for today's climate is 276 m^3/s (Persson et al, 2014). According to a climate analysis for the county, precipitation will increase by approximately 20% until year 2100, with the most profound increase during the winter month. As well will the frequency and intensity of rain burst increase (Persson et al, 2014). The climate scenarios do not consider future river flow regulations.
There is no sediment transport data for the river and bathymetric data is limited to a few sounded cross sections for the southern part of the river. Overall, there is very little knowledge of the river characteristics, especially below the water surface.

2.2 Governing equations

The main assumption for the erosion model is that formulas for cohesive sediments should apply for River Norsälven. The general formula for erosion rate in cohesive sediments is written as (Hanson and Cook, 1997; Hanson, 1990; Partheniades, 1965)**:**

$$E = k_d(\tau_0 - \tau_c)^a \quad (1)$$

Where E is erosion rate (m s^{-1}), k_d is the erodibility coefficient ($m^3N\ s^{-1}$), τ_0 is the average boundary shear stress (Pa), τ_c is the critical shear stress (Pa) and α is generally considered to be 1. The formula may seem simple but the parameters are very difficult to determine without comprehensive in-situ field measurements (= expensive). It requires a large field effort with great resources which have not been possible for the case. Instead, the values of k_d and τ_c must be based on empirical studies reported in the literature. Hanson and Simon (2001) conducted 83 submerged jet-tests to find an empirical relationship between τ_c and k_d for cohesive silts, silt-clays and clays. They conducted the tests for a wide variety of soils in mid-western United States, with τ_c varying from 0,0 to 400 Pa and k_d varying from 0,001 to 3,75 $m^3N\ s^{-1}$ and developed the following relation:

$$k_d = 2 \cdot 10^{-7} \tau_c^{-0,5} \quad (2)$$

Jet-testing on bank toes suggests that although the exponent is the same, the coefficient is instead 1×10^{-7} (USDR-ARS, 2015):

$$k_d = 1 \cdot 10^{-7} \tau_c^{-0,5} \quad (3)$$

In 2010, Simon et al. refined their analyses (eq. 2) with improved field instrumentation and performed about 1100 jet-tests in fine grained soils from 16 states within the US and compared to earlier results and found the following relation:

$$k_d = 1{,}6 \cdot 10^{-6} \tau_c^{-08264} \quad (4)$$

Karma and Dutta (2011) conducted 58 submerged jet-tests and found that there are a few outlier data points for which it is not possible to fit the data with simple regression. In their case, the robust regression technique they used gives less weights to the outliers and so the results are less sensitive to these outlier, a better fitting is hence given and with higher correlation (p=0,002):

$$k_d = 3{,}16 \cdot 10^{-6} \tau_c^{-0{,}185} \quad (5)$$

Hanson and Simon (2001) carried out their tests in the river bed, while the study by Karma and Dutta (2011) was carried out for the river banks.
There are other studies (see for example Wynn, 2004) but regardless the method, an estimation of k_d assumes that there is no deposition of the bank material near the bank. In contact with the USDA-ARS (Langendoen, 2014), the equations relating k_d to τ_c are based on data with a lot of scatter. The coefficient and exponent of the relation can vary quite a bit and a re-analysis by Rob Thomas of Andrew Simon's original data (plus many more, Simon et al., 2010) resulted in slightly different values of coefficient and exponent. The range in values reflects the heterogeneity of soils, effects of organics, moisture conditions, etc. According to Langendoen (2014) he typically fit a k_d to τ_c curve through the site-specific, measured

data to remove scatter. These curves can have quite different values than reported in literature. Also, the k_d itself is often slightly modified to obtain better agreement between observed and predicted erosion rates. In summary, there is a lot of uncertainty in the used k_d value but if one get good agreement with eq. 3, it is suggested to use that to evaluate our study objectives (Langendoen, 2014).
Erosion for a given time period is then calculated through the following equation (e.g. Partheniades, 1965; Karmaker and Dutta, 2011; USDA-ARS, 2015):

$$E_t = k_d(\tau_0 - \tau_c)^a \cdot \Delta t \qquad (6)$$

Where E_t is erosion (m) for a given time period and Δt is the total time for fluvial erosion (s). This is based on the assumption of constant conditions, i.e. no changes in flow or shear stress etc. It is in general believed that it is the bankfull discharge (i.e. the flow when the river is just about to spill onto its floodplain) that most effectively shape river channels (e.g. Karmaker and Dutta, 2011; Maidment, 1992).
For the case, it is further assumed that if fine sediment is eroded from the river bed, it is not likely that it deposits in the river but is transported to the lake where the river debouches. If one also neglects accumulation, the estimate of erosion in the river is on the safe side.
The average boundary shear stress (τ_0) is an index of the force that the flowing water exerts on the bottom and is therefore closed linked to the flow velocity. Normally, and for turbulent flow, τ_0 is assumed proportional to water velocity squared. Average boundary shear stress for a wide stream (with larger than depth) (e.g. Chanson, 2004):

$$\tau_0 = \rho g d sin\theta \qquad (7)$$

Where ρ is the density of the water (kg/m^3), g is the gravity force (m/s^2), d is flow depth (m) and $sin\theta$ is the longitudinal bottom slope (-). Equation 7 can then be rewritten by introducing Manning's formula (Larson, 2014):

$$\tau_0 = \frac{n^2 \rho g v^2}{\sqrt[3]{d}} \qquad (8)$$

Where n is Manning's roughness (s/m^3) and v is the water velocity (m/s).
One of the first and most known formulas to estimate critical shear stress is the one based on Shield's parameter and D_{50} (see for example Chanson, 2004). However, none of these are valid for cohesive sediments. Experimental studies that are based on empirical relations between critical shear stress and different sediment characteristics have shown that it is possible to estimate τ_c from the proportion of fine sediments. These studies are presented in Karmaker and Dutta (2011) and have been developed by Dunn (1959), Vanoni (1977) and Julian and Torres (2006):

$$\tau_c = 0{,}1 + 0{,}1179(SC) + 0{,}0028(SC)^2 - 2{,}34E^{-5}(SC)^3 \qquad (9)$$

Where SC is the percentage content of silt and clay fraction in the sediment (hence the abbreviation S and C).
In this study, total time for fluvial erosion concerns a prognosis of the re-occurrence of erosive discharges with respect to the effects of climate change in the study area.

2.3 Data

Bathymetric data from different time periods are by far the best data to make prognosis of future changes of river morphology. Also sediment transport data is of good use. However, for the Swedish rivers such data are rarely available, at most you can find information on river flow from the hydropower plants and water levels at some points. Sounding cross sections can be available near settlements and where geotechnical investigations have been made. The collection of existing data covered surface geology, surface topography, sounded cross sections (cross profiles), flow statistics from 1971 until 2013, sections with erosion protection, and climate scenarios until year 2100.
Recent investigations includes *i*) diachronic analysis in GIS of aerial photos from 1965/66

and 2013 to investigate shoreline displacement over time, *ii*) a bathymetric survey (hydro acoustic soundings) with sediment sampling and analyses to yield a bathymetric map and a general marine geological map, *iii*) a 2-dimensional hydrodynamic model to model average shear stresses, depth integrated water velocities, water depths and water levels for different river flows and *iv*) geotechnical surveys in cross sections for the analysis of soil mechanical properties.

The diachronic analysis was done by the Swedish Geotechnical Institute (SGI), the bathymetric survey was done by Marin Miljöanalys AB, sediment analyses was done at the SGI laboratory, the hydrodynamic modelling was done by the Swedish Meteorological and Hydrological Institute (SMHI), and the geotechnical surveys were done by Norconsult (Bergdahl et al, 2015). All data, except for the geotechnical surveys, was delivered as GIS layers.

A marine geological map was constructed based on backscatter data and sediment analyses from the bathymetric survey. Critical shear stresses for these sediments were calculated with eq. 9 to convert the marine geological map into a critical shear stress map.

Average shear stresses was simulated for 11 discharges (20, 70, 150, 200, 250, 300, 350, 400, 450, 500 m^3/s).

Former cross sections were digitalized in CAD and compared with the new bathymetry. Of 21 former cross sections, only four were assessed useful for further analysis (no dredging, no erosion protection, and no accumulation of sediments). These sections had been sounded in 1971. By analyzing the changes (erosion) in these cross sections from year 1971 until 2013, the equation for k_d (eq. 2-5) and the most probably erosive river flows could be chosen. Average shear stresses (τ_0) were obtained from the hydrodynamic model and critical shear stresses were obtained from the converted backscatter data. If calculated erosion according to eq. 6, and by varying flow scenarios and the equations for k_d, did not differ more than ± 0,5-1 m from the measured, it was assumed a good enough agreement.

An estimation of the time for fluvial erosion (Δt) is based on historical data and information on future river flows with respect to the effects of climate change.

2.4 Models

Two models were set up, one GIS model to compute surface covering bed erosion, and one spreadsheet model to compute bank and bank toe erosion in chosen cross sections as the GIS model do not capture the erosive processes that act on the bank and bank toe. The spreadsheet model for bank and toe erosion is only used to simulate changes in bank geometry and not to calculate slope factor of safety, although possible. The reason is that the spreadsheet model uses a slightly different approach compared to the national instructions. To clarify, changes in geometry in chosen cross sections were obtained from the GIS model and the spreadsheet model, and were then inserted into a model for geotechnical solutions to calculate slope factor of safety. Slope factor of safety was hence calculated for today’s geometry and for a future forecasted change in geometry, but also for a change in groundwater tables (change in groundwater table from climate change is not included in this paper). The cross sections were chosen to represent different geological and geotechnical units along the river. The GIS model, together with the diachronic analysis, was used for a surface covering prognosis of areas with future erosion and a prognosis of the extent.

3 RESULTS

3.1 Parameter setting for case Norsälven River

Based on the backscatter data the bottom surface sediment was divided into four sediment types and for which critical shear stresses were calculated (Table 1 and figure 2).

Table 1. Classification of backscatter data into sediment type and critical shear stresses.

Backscatter dB-range	Soil classification	Color code in GIS	Critical shear stress (Pa)
0-54	Silty clay	Grey	0,26
54-65	Sandy silt	Yellow	0,21
65-87	Silty sand	Orange	0,14
87-120	Gravel, stone, bedrock	Red	>5

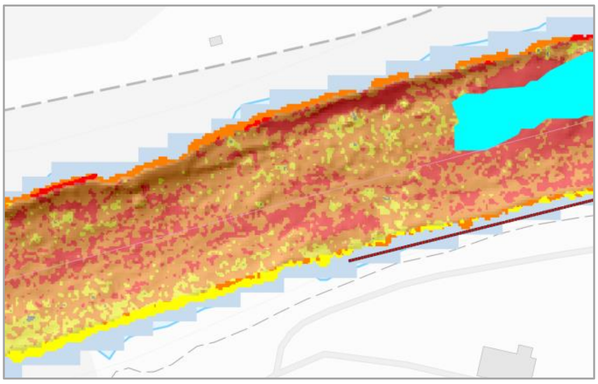

Figure 2. Extracts from GIS showing the interpreted sediment types from backscatter data. The blue areas are presumed bedrock. The red lines are erosion protection. © SGI, Lantmäteriet, Geodatasamverkan.

A new spreadsheet model was set up to carry out the calculation of governing equation for k_d and erosive flow based on the comparison of cross sections from 1971 and the bathymetry from 2013. Equations 4 and 5 could not describe the measured erosion in the analyzed cross sections and the deviation was several meters, sometimes tens of meters. Equation 2 and 3 gave equivalent results and with an accuracy of up to one meter. Both eq. 2 and 3 are used by USDR-ARS (2015) but according to Langendoen (2014), eq. 3 is preferable if it yields good correlation. By using eq. 3, the erosive flow seems to start somewhere below 300 m^3/s, maybe a bit lower but not as low as 250 m^3/s (the hydrodynamic model was not simulated for flows between these levels). Other flows are possible but the variation in results is greater.

Regardless of the equation for k_d and the value of flow that is used, it will not be possible to describe all changes of river geometry but hopefully where a majority of the changes will take place and the approximate size.

It was not possible within the commission's budget limit to conduct a separate climate scenario analysis to answer the project specific issue, meaning that existing information had to be used. For the case, a climate analysis for the County administrative board of Värmland was available (see Persson et al., 2014).

The climate analysis was based on 16 climate scenarios and is made with respect to the reference period 1963-1992, the period 2021-2050 and the period 2069-2098. The results from the analysis shows for instance seasonal water flows, with marks for all scenarios mean flows, the 25 percentile and 75 percentile water flows, and for the three time periods (Persson et al., 2014), see Fig. 3.

The mean flow will never reach as high as the estimated erosive flows, meaning that changes in the mean flow will not be possible to use in order to determine the time for fluvial erosion (Δt). However, it might be possible to use changes of the 75 percentile from the reference period until 2098 and with respect to the erosive water flow, and superimpose that change to the frequency of erosive flows between the years 1971-2013.

The most likely erosive flow seems to be slightly below 300 m^3/s. In order to estimate the number of days for critical erosive flow, both 300 and 275 m^3/s has been used. The following equation was set up:

$$\Delta t = T \cdot f_{Qe} \cdot F_{Qe} \qquad (10)$$

Where Δt is the duration of future erosive flows (d), T is the number of days until future (here, the number of days between 2014-2100), f_{Qe} is the percentage of days between 1971 and 2013 with erosive flow, and F_{Qe} is the increase of the percentage of days with erosive flows until 2100 and based on an increase in 75 percentile flow of all the climate scenarios max values and with respect to the reference period (Fig. 3). The number of days between 2014 and 2100 is 31412 days taking into account leap years, f_{Qe} was estimated to 0,35% based on flow statistics from the years 1971-2100 (Q≥300 m^3/s occurred ca 47d, Q≥275 m^3/s occurred ca 61d) and F_{Qe} was estimated to 34% (approximately the mean value of an increase by 10% of Q ≥300 m^3/s and an increase by 58% of Q≥275 m^3/s). With this approach, Δt is estimated to 150 days.

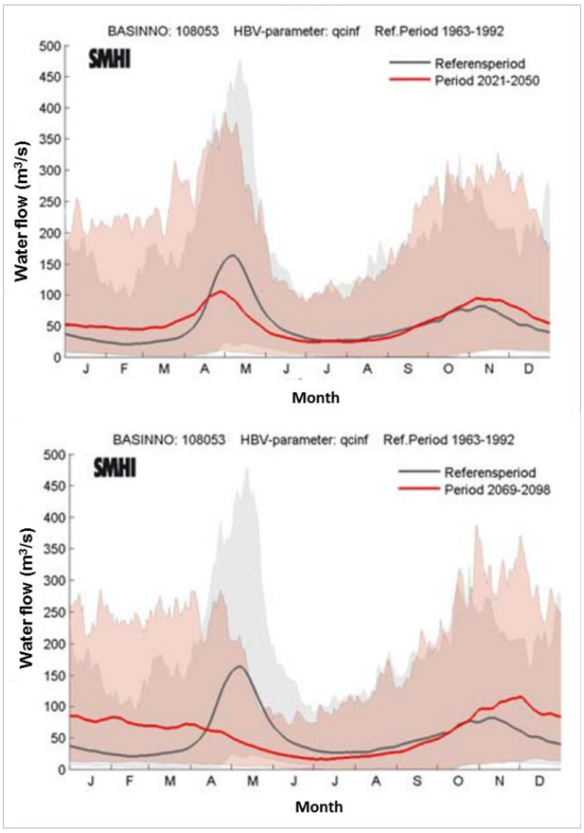

Figure 3. River flows for Norsälven River showing seasonal dynamics for the mean flows for the reference period 1963-1922 (black line) and for the two future time periods (red line). The grey shade shows the variation between the 75 percentiles of all scenarios max values and the variation between the 25 percentiles of all scenarios min values for the reference period. The light red shade shows the same but for the future time periods (2021-2050 and 2069-2098) (in Persson et al., 2014).

3.2 Bed erosion

The GIS layers for parameter setting comprises average shear stresses (5×5 m raster, tif format), critical shear stresses (0,5×0,5 m raster, tif format), a bedrock mesh (vector, shp format) and a watercourse mesh (vector, shp format) for delimitation of output file. The erosion calculation then contains a number of steps to prepare the data, customize the grid and perform the actual calculation according to eq. 6.

Figure 4 displays an example of the output file that shows a prognosis of bed erosion in the river until 2100 considering the effect of climate change with increased river flows.

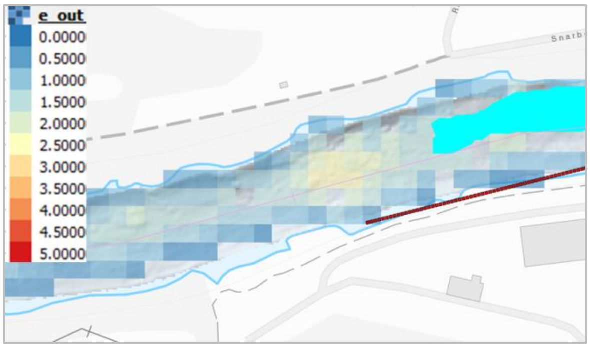

Figure 4. Extracts from GIS output file that shows calculated bed erosion (m) in half meter intervals and for 10×10 meter grids. The figure only displays a minor part of the river stretch. © SGI, Lantmäteriet, Geodatasamverkan.

3.3 Bank erosion

Bank erosion and changes of bank geometry for chosen cross sections were calculated by using the spreadsheet model for bank and toe erosion and combining it with the results from the GIS model to include bed erosion. Input data on geometry and bank material (cohesion, friction angle, saturated unit weight) was obtained from the geotechnical surveys. A limitation in the spreadsheet model for bank and toe erosion is that bank material can only be added as horizontal layers and inclined layers hence had to be modified to horizontal layers.

Data on channel and flow parameters should be added in order to compute average shear stresses but in this case we already have the shear stresses from the hydrodynamic model. Hence, we were sent a version with one of the tabs in the spreadsheet model unlocked (toe model) which made it possible to fit the channel and flow parameters to desired values on τ_0.

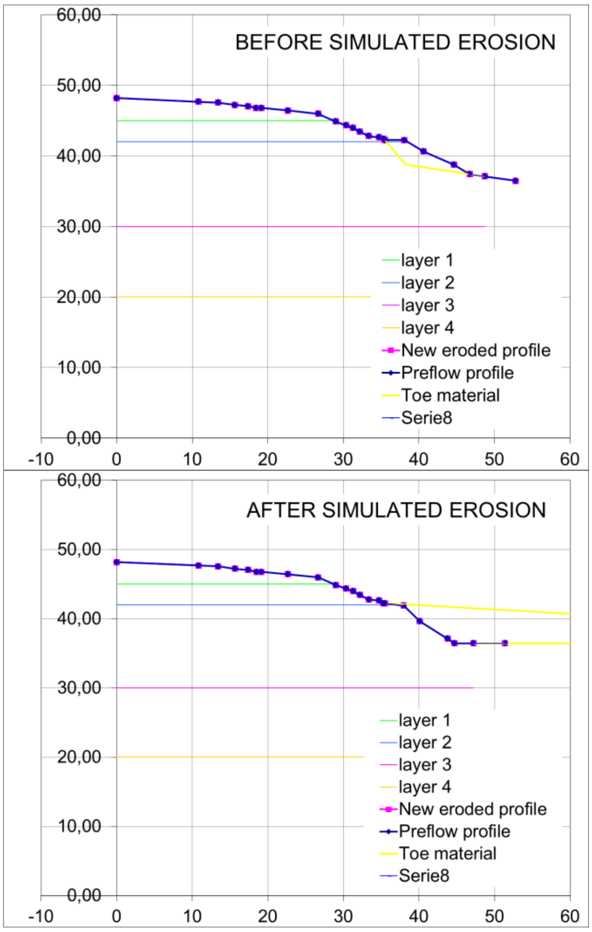

Figure 5. Example of output file from input geometry and simulated bank and toe erosion in the spreadsheet model. The blue line with pink squares represents the original and the eroded profile, respectively. The colour lines represent different sediment characteristics.

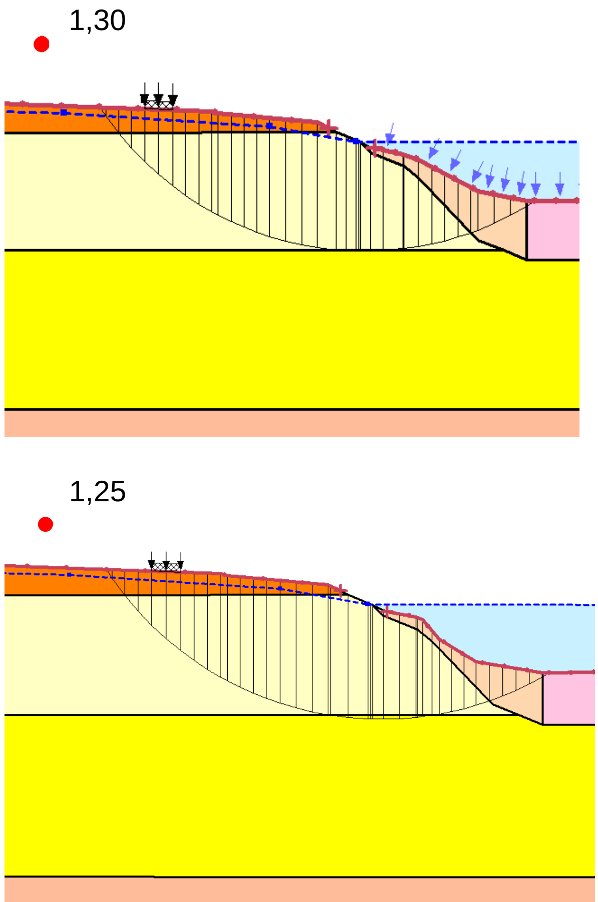

Figure 6. Example of prognosis of future changes in bank and bed geometry for a cross section until year 2100 and considering future erosion from the effects of climate change. The upper figure shows original geometry and factor of safety and the lower shows the factor of safety after simulation of future erosion.

It is possible in BSTEM to simulate erosion in time steps but we had problem to make it work.

Figure 5 displays an example of an output file in BSTEM after simulation, and Fig. 6 displays an example of prognosis of changes in bank and bed geometry for a chosen cross section.

3.4 *Assessment of reliability*

The reliability of calculated prognosis of bank erosion until year 2100 can only briefly be verified. By comparing the results with the results from the diachronic analysis of shoreline displacement, the reliability of the calculated bank erosion could be assessed. Cross sections that resulted in a clear bank retreat until 2100 had historically (since year 1965) undergone erosion according to the diachronic analysis. And vice versa, cross sections that resulted in no bank retreat showed the same in the diachronic analysis. Calculated bed erosion was compared with historically bed erosion from the comparative study of earlier and recent sounding, however, the same was used to determine parameter values for the calculation which could give circle evidence. There is one exception though, and that is very close to the hydropower plant where a too low value of the critical stress probably was chosen as the bed consists of bedrock. The calculated future erosion indicates almost 9 m erosion until 2100 which is not reasonable.

The yearly land upheaval of ca 3 mm/year (0,26 m until 2100) has not really been taken into account since the resolution in the calculation is within 0,5-1 meter. This could of course be discussed.

The result from the forecasted bed and bank erosion were implemented in the slope stability calculation and the assessment of landslide probability which then resulted in landslide risk maps with different dashed patterns in the river area showing low, moderate or high impact of climate change on landslide probability (not included in this paper).

4 DISCUSSION

This paper describes an approach to make a prognosis of future river bed and bank erosion considering the effect of climate change as a basis for the assessment landslide risk by year 2100. There are no models available for this kind of forecasting that combines soil mechanical forces with hydrodynamic processes. In this study, we therefor used GIS to model future bed erosion and a spreadsheet based model to model future bank erosion in cross sections. The study site is the river Norsälven River in Sweden. Cohesive sediments are dominating the geological feature.

The calculated erosion rate depends partly on the differences between current τ_0 and τ_c, and partly on the duration of this τ_0. High river flows yield larger difference between τ_0 and τ_c but with shorter duration. On the contrary, low flows yield smaller differences between τ_0 and τ_c but longer duration since flows close to the mean occur more frequent than the extremes. Bankfull discharge is often mentioned as the stage with most effective erosion. The bankfull discharge can however be difficult to determine and for the case we used flow scenarios to described measured erosion, i.e. the flows that can explain the measured erosion.

One important uncertainty is that only four former sounded cross sections could be used to measure historical changes in bathymetry and it would have been desirable with more. These four sections were sounded in 1971 and we do not really know which sediment that has eroded away until 2013 when new measurements were made. However, the absence of data is often the case for rivers in Sweden and we have to deal with it.

None of the empirical equations to determine k_d have been able to describe the measured erosion completely accurate. Nevertheless, it has been possible to exclude the equations that were definitely not right. If the chosen equation for k_d and the chosen critical shear stresses could describe the measured erosion by ± 0,5-1 m it was assessed good enough to meet the objectives and considering the many uncertainties, especially with climate scenarios. One possibility could have been to work more with uncertainties and visualize them clearly.

It was not possible to forecast erosion stepwise; consequently, changes in bed condition and sediment characteristics could not be updated. Erosion does not occur at a steady pace, but at single flow peaks. After each erosion event, the geometry is changed and the prerequisite for further erosion is changed especially if erosion causes bank failure.

To conclude, we find the approach useful but cumbersome and there emphasize the need for the development of models and softwares that are able to manage soil mechanics AND hydrodynamics. There are river morphological models available but these models comprise only the river itself and not the adjacent land area with its geological feature and soil properties. We also would like to emphasize the need for repeated bathymetric measurements, not only for the validation of the models but to gain control of erosion and erosion processes. Such data is invaluable.

5 ACKNOWLEDMENT

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