Multi-hazard: Contaminated land vulnerable to natural hazards and effects of climate change

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ABSTRACT
Erosion, slope failure and flooding of contaminated land is a not yet recognized multi-hazard that needs consideration in land use planning. Most cities have developed in the vicinity of surface waters (rivers, lakes, and coastline) and it is also adjacent to these waters most industrial activities have been located and still are. The surface water has been used for transportation as well as recipient for the release of waste waters. Leakage, continuous emissions and accidental spills from hazardous activities have caused the contamination of soils, groundwater, surface waters and sediments. Natural hazards are effective pathways for the release and wide spreading of contaminants from these sites to the ecosystem. Regions experiencing an increased precipitation due to climate change may be exposed to an increased threat from such multi-hazards. Together with Lund University of Technology and Chalmers University of Technology, the Swedish Geotechnical Institute (SGI) conducted research to obtain knowledge on the spreading of pollutants from landslide into rivers and to develop a model framework that can serve as a complement for landslide risk assessments and environmental risk assessments. The results show that there are several contaminated sites that are located on unstable ground and that a landslide induced release of contaminants can cause a clear increase in pollutant concentration in surface water (Göransson, 2013, Göransson et al., 2013). Between year 2014 and 2015, SGI developed and tested a GIS based quick scan method at a river basin scale to identify contaminated sites that may be vulnerable to natural hazards. In addition, a method was developed and tested to assess a specific contaminated site´s vulnerability to natural hazards, including increased precipitation due to climate change (Edebalk et al., in press). The purpose is then to implement these methods as complement to existing methods for risk assessment.

Keywords: Contaminated soil, landslide, erosion, flooding, climate change

1 INTRODUCTION

Contaminated land poses risk for human health and the environment. In Sweden, the national environmental quality standard sets the direction for the environmental work to reduce risks. There are many contaminated sites in Sweden and the investigation and management of contaminated land areas is an important part of the environmental work. A national inventory has been done to identify potentially contaminated sites and until now about 80 000 sites have been identified. Each site has then been risk assessed and classified as posing minor, moderate, high or very high risk, based on type of pollutants and their distribution in the soil.
Although urban areas and industrial sites are commonly located adjacent to surface water, very few studies have paid attention to the risk of mobilization and spreading of pollutants to surface water due to natural hazards like landslides (Göransson et al. 2012). Natural hazards globally strike urban areas yearly but only few studies have looked upon the environmental consequences after

such events (see UNISDR and data statistics at http://www.unisdr.org/we/inform/disaster-statistics).
Methods for the risk assessment of natural hazards include the assessment of the vulnerability to humans, infrastructure, buildings and the environment. Except for flooding, damage to the environment has mostly been about the loss of valuable flora and not damage to hazardous facilities (see for example Bonnard et al., 2004). Likewise, existing methods for environmental risk assessment do not consider natural hazards as potential pathways for catastrophic spreading of contaminants.
Contaminated land is the contamination of soil and (ground) water and is caused by the presence of chemicals or other alteration in the natural soil environment. Soil contamination is usually caused by industrial activities (leakage, spills, and waste disposal), improper waste disposal, agricultural chemicals, urban activities (e.g. waste water) etc. Many of the contaminated sites are located adjacent to surface waters (lakes, rivers, and coasts) for energy production, transportation, receiving waters, and cooling. However, waterfront areas may be exposed to natural hazards.
Landslides, debris flows, erosion and flooding mean that soil is mobilized and transported although in different temporal and spatial scales. Landslides are the rapid movement of soil and rock that occur almost without warning and causes great damage. Erosion is the detachment, transport and deposition of soil particles, usually by running water. Flooding is the overflow of water that submerges land which usually is dry.
A landslide of contaminated soil into surface water will instantaneously release a great amount of contaminants into the water, and over time through erosion and diffusion from contaminated run-out deposits (Göransson, 2013). Continuous bank erosion can cause a diffuse and continuous spread of contaminants to the water (Rhoades et al., 2009; Rowan et al., 1995). The extent of erosion depends on soil type, density, vegetation, flow velocity, and how the water currents affect the slope (Wynn and Mostaghimi, 2006). Erosion can be a trigger for landslide, flooding may enhance erosion, and rainfall can cause flooding but also trigger landslides (Glade, 2003; Pradhan et al., 2012; Van Asch et al., 1999). Flooding of contaminated sites causes leakage of contaminants that are spread further by the water (Dennis et al., 2003). Flooding also can cause increased groundwater level and leakage and spread of contaminants with the groundwater flow. A change (increase) in precipitation (frequency, intensity) affects surface run off and groundwater level. This may in turn change the prerequisites for the spreading of contaminants in the soil to recipients.
The aim of this paper is to highlight the combined risk of natural hazards and contaminated land and to present an approach for identification and vulnerability classification of the hazard at different scales. The overall objective is to develop an approach for the assessment of contaminated site's vulnerability to natural hazards that includes not only landslides but also erosion, flooding and increased precipitation from climate change.

2 METHOD

The papers by Göransson et al. (2009; 2012 and 2013) are the first to highlight the combined risk of contaminated soil at landslide risk. The first paper (Göransson et al., 2009) identified the combination of landslides and contaminated land as a multi-risk and suggested a conceptual model for the governing processes. The second paper (Göransson et al., 2012) applied a non-dimensional advection-dispersion equation for the description of possible sediment and subsequent contaminant transport for the instantaneous release of contaminants from landslides. The third paper (Göransson et al., 2013) suggested a methodology to estimate the environmental risks associated with landslide in contaminated sites adjacent to rivers.
In this paper, an approach is presented that includes three methods based on scale and level of detail in background information. The approach includes methods for quick

scan hazard identification that can either be done at a larger geographical scale (river basin) or at a local scale from a single object. The criterion has been that the approach should be based on existing digital data and that the results could be used as a basis for priority between sites for detailed investigations. Thus, access to data in the GIS format has therefore been governing. The third method for risk estimation is under development and a first conceptualization is presented.

2.1 Quick scan method for hazard identification at a river basin scale

Screening over a larger geographical area for the identification of contaminated sites exposed to natural hazards aims to make a general and rapid assessment of potential risk as a basis for prioritization for detailed investigations and risk assessment.
The method is based on the ability to connect already existing GIS layers with each other, thereby quickly and easy identify where within a larger geographic area (e.g. river basin) the combination of contaminated land areas and areas exposed to natural hazards occur. The consequences of increased precipitation from climate change have not been included at this scale in this study since no spatial GIS layers were available at the time, but can be done.
The GIS method is based on the identification of contaminated sites whose geographical location coincides with the known locations of areas of potential landslide, bank erosion and/or flooding. The method is designed so that the minimum amount of data should provide useful results. Additional data could advantageously be included to increase the reliability of the identification. In Sweden, the basic GIS layers for the method are available through Geodata (www.geodata.se). Additional layers can be search for at different authorities. See Table 1 for specification.
Manual processing is in general required to adapt some of the data before the GIS identification procedure can be run. For example, some of the data is delivered as point information or lines. Such data need to be converted to surfaces.

Table 1. Data base for the GIS identification process.

	Product	Supplier
Basic data	Potentially contaminated sites	The County Administrative boards
	Property map	Lantmäteriet
	National elevation data, GSD	Lantmäteriet
	Flood map	Swedish Civil Contingencies Agency
	Soil map	Swedish Geological Survey
	Map: prerequisites for landslide	Swedish Geological Survey or Swedish Geotechnical Institute
	Map: prerequisites for erosion	Swedish Geotechnical Institute
	Active erosion	Swedish Geotechnical Institute
Additional data	General moraine landslide hazard zonation map	Swedish Geotechnical Institute
	General slope stability hazard zonation map	Swedish Civil Contingencies Agency
	Landslide database	Swedish Geotechnical Institute
	Gully and landslide scar data	Swedish Geological Survey

2.2 Quick scan method for vulnerability assessment of a single object

The method is based on a single object, i.e. a contaminated site that has undergone an environmental risk classification or environmental risk assessment. The aim is here to identify if the site also may be exposed to an increased risk for contaminant transport in the event of natural disaster.
The most likely scenario is that the vulnerability for natural hazards are observed for contaminated sites that have been classified as having high or very high environmental risk, or that are facing measures or land development.
The suggested method aims to gather all existing data on soil movement (slope stability), erosion, flooding and change in precipitation, and to make an overall assessment of whether there is negligible, minor, moderate or major vulnerability for each of the natural hazards to the contaminated site. The method is hence

divided into the following natural hazard categories:

- Soil movement (landslide, debris flow)
- Bank erosion
- Flooding (lakes, rivers, coasts)
- Increased precipitation from climate change

Assessment matrices have been developed for each of the categories. The matrices and the approach how to use these are briefly described below.

The geotechnical data for the assessment of a contaminated site's vulnerability to soil movement may consist of geotechnical investigations (general, detailed, in-depth) or general landslide hazard zonation maps. The available data with maximum degree of detail should be used. Table 2 shows the assessment matrix for geotechnical investigations, based on the national requirements for stability investigations. If a geotechnical survey is available, the lowest value on the slope safety factor should be used in Table 2 to assess vulnerability. Assessment matrices are also available for data in the form of general landslide hazard zonation maps for fine-grained and coarse-grained soils respectively, and maps showing the prerequisites for landslide in fine-grained soils. Table 3 shows the assessment matrix for the assessment of a contaminated site's vulnerability to soil movement if the site is located on fine-grained soil and if only a general slope stability hazard zonation map is available.

In contrast to the above, there is no national method to map bank erosion. The assessment of vulnerability to riverine, lake or coastal erosion is therefore based on soil type and the contaminated sites distance to beach. The sensitivity to erosion varies with soil type and silt and sand are considered the most erosive soils. Hence, the basic data consists of the soil type map. Table 4 shows the assessment matrix for erosion.

Table 5 shows the assessment matrix for the assessment of a contaminated site's vulnerability to flooding. In Sweden, general flood risk mapping (in fact, flood hazard zonation mapping) are performed by the Swedish Civil and Contingencies Agency. Flood risk maps exist for many of the watercourses in Sweden but not for all. There are updated risk maps of particularly urgent rivers regarding climate change and climate scenarios until year 2098.

The flood risk maps show areas flooded at different return periods of flows, usually 100-year floods. In addition, there are areas marked which can be flooded by a theoretically calculated maximum flow. The updated maps regarding climate change effects also show areas flooded at 50-year return period and climate adapted 100-year floods and 200-year floods. Areas that are flooded already today are considered to have the highest vulnerability.

If there is no flood risk mapping for the case under study such needs to be developed. General flood risk mapping for the coastal areas are only available for Scania and has been developed by the County Administrative Board of Scania. The mapping is based on mean sea water level and high water level for today's situation and future levels with respect to climate scenarios. Also, the Swedish Meteorological and Hydrological Institute (SMHI) has developed a rough map that shows the net effect of sea water level, minus the effect of land upheaval, along the Swedish coast line, and at a global sea water level rise of 1 m until year 2098.

In this study we use climate scenarios for a change in annual mean precipitation as an indicator for the assessment of whether a future change in precipitation may affect the spreading of contaminants.

The level of precipitation increase is arbitrary set to be used together with SMHI's climate scenario maps (available at www.smhi.se). The data is used only as a check that consideration should be taken to changes in precipitation (annual, intensity and frequency). Climate scenarios are displayed as RCPs (Representative Concentration Pathways). RCPs are scenarios of how the greenhouse effect will be enhanced in the future. The RCP scenarios are based on levels of anthropogenic radiative forcing, expressed in watts per square meter. The RCP scenarios are termed with the radiative forcing achieved in year 2100: 2,6, 4,5, 6,0 or 8,5 W/m^2 (https://www.ipcc.ch/report/ar5/).

Table 6 shows the suggested assessment matrix that can be used to assess the vulnerability to increased precipitation. In that matrix, RCP 4,5 has been chosen as the future scenario, but it is possible to use any of the scenarios.

Table 2. Assessment matrix for the assessment of a contaminated site's vulnerability to soil movement when geotechnical stability investigations are available for the contaminated site. The table shows how different values on slope safety factor should be interpreted depending on the investigation's level of detail. F_c = total factor of safety, undrained analysis F_k = total factor of safety, combined analysis, F_φ = total factor of safety, drained analysis, F_{EN} = factor that uses partial coefficients.

Data	Negligible vulnerability	Minor vulnerability	Moderate vulnerability	Major vulnerability
In-depth/additional geotechnical slope stability investigation	$F_c > 1,8$ $F_k > 1,7$ $F_\varphi > 1,5$	$1,5 < F_c \leq 1,8$ $1,4 < F_k \leq 1,7$ $1,3 < F_\varphi \leq 1,5$	$1,25 < F_c \leq 1,5$ $1,2 < F_k \leq 1,4$ $1,15 < F_\varphi \leq 1,3$	$F_c \leq 1,25$ $F_k \leq 1,2$ $F_\varphi \leq 1,15$
Detailed geotechnical slope stability investigation	$F_c > 2,2$ $F_k > 1,8$ $F_\varphi > 1,5$	$1,7 < F_c \leq 2,2$ $1,5 < F_k \leq 1,8$ $1,3 < F_\varphi \leq 1,5$	$1,3 < F_c \leq 1,7$ $1,25 < F_k \leq 1,5$ $1,15 < F_\varphi \leq 1,3$	$F_c \leq 1,3$ $F_k \leq 1,25$ $F_\varphi \leq 1,15$
General geotechnical slope stability investigation	$F_c > 3,0$ $F_k > 2,0$ $F_\varphi > 1,8$	$2,0 < F_c \leq 3,0$ $1,6 < F_k \leq 2,0$ $1,5 < F_\varphi \leq 1,8$	$1,5 < F_c \leq 2$ $1,3 < F_k \leq 1,6$ $1,3< F_\varphi \leq 1,5$	$F_c \leq 1,5$ $F_k \leq 1,3$ $F_\varphi \leq 1,3$
Slope stability investigation based on the method for partial coefficient (F_{EN}) (Eurocode)	The intervals above apply by multiplying F_{EN} for undrained analysis with 1,5 and F_{EN} for drained analysis with 1,3. There is no conversion factor for combined analysis.			

Table 3. Assessment matrix based on general slope stability map for fine-grained soil for the assessment of a contaminated site's vulnerability to landslide.

Data	Negligible vulnerability	Minor vulnerability	Moderate vulnerability	Major vulnerability
General slope stability zonation map, fine-grained soils.	*White zone on stability map.* Areas judged to be satisfactory stable under prevailing conditions.		*Yellow zone (or yellow with black diagonal lines) on stability map.* Areas previously considered satisfactory stable but that do not follow today's requirements for investigation. Areas in need of review of earlier investigations or measures, especially for areas marked with black lines.	*Orange zone (or orange with black diagonal lines) on stability map.* Areas judged not to be satisfactory stable. Areas in urgent need of detailed investigations, especially for areas marked with black lines.

Table 4. Assessment matrix for the assessment of a contaminated site's vulnerability to erosion.

Data	Negligible vulnerability	Minor vulnerability	Moderate vulnerability	Major vulnerability
General inventory of the prerequisites for bank erosion	Bedrock/stable ground, erosion protection OR ≥ 200 m to the beach.	Clay OR 100-200 m to the beach.	Sand, silt, flood plain deposits, fill, OR visible erosion in clay AND < 100 m to the beach.	Visible erosion/active erosion in sand, silt, flood plain deposits.

Table 5. Assessment matrix for the assessment of a contaminated site's vulnerability to flooding. CMF = calculated maximum flow, Q_{200} = 200 year flood, Q_{100} = 100 year flood, Q_{50} = 50 year flood, MHWL = mean high water level, MWL = mean water level, GL = ground level, masl = meter above mean sea water level.

Data	Negligible vulnerability	Minor vulnerability	Moderate vulnerability	Major vulnerability
Updated flood risk maps with regard to climate change - rivers	Outside Q_{200} marked area (climate adapted flow)	Within Q_{200} marked area but outside Q_{100} (climate adapted flow)	Within Q_{100} marked area but outside MHWL or Q_{50} (climate adapted flow)	GL < MHWL OR within Q_{50} marked area (climate adapted)
General flood risk maps - rivers	Outside CMF marked area	Within CMF marked area but outside Q_{100}	Within Q_{100} marked area but outside MHWL	GL < MHWL OR within Q_{100} AND GL ≤ 1 MWL
General flood risk mapping - coast	GL ≥ 5 masl	3 masl ≤ GL < 5 masl	1 masl ≤ GL < 3 masl	GL < 1 masl OR prone to flooding today.

Table 6. Assessment matrix for the assessment of a contaminated site's vulnerability to increased precipitation. P_i = increase in mean annual precipitation until 2098 and compared with the reference period 1961-1990.

Data	Negligible vulnerability	Minor vulnerability	Moderate vulnerability	Major vulnerability
Change in precipitation, climate scenario RCP 4,5	P_i < 5%	5% ≤ P_i < 10 %	10% ≤ P_i < 15 %	P_i ≥ 15%

The assessments carried out based on the above mentioned assessment matrices is gathered in an overall assessment matrix for an overview of the natural hazards that have been identified for the contaminated site. A summarized assessment is done to assess the overall need for further investigation/action for each of the identified hazards by filling in the information in a summary matrix (see further the example in 3.2). The need for additional investigation for each of the natural hazard is determined according to:

- Negligible vulnerability: No need for further investigation
- Minor vulnerability: The site cannot be disclaimed from natural hazards, control is needed.
- Moderate vulnerability: A need for in-depth risk assessment regarding identified natural hazard(s), probable need for action.
- Major vulnerability: Urgent need for in-depth risk assessment regarding identified natural hazard(s). A need for action.

2.3 Proposed method for risk estimation of a single object

In Göransson et al. (2013) a probabilistic method was developed to estimate possible environmental risks from landslide of contaminated soil into rivers in order to allow for datasets with large uncertainties and the use of expert judgements. Consequences were divided into impact zones for the estimation of possible consequences in the near-field, along the pathway (river) and in the accumulation area (e.g. estuary, lake). Consequences were assessed in terms of failure for exceeding certain environmental quality standards since there are no studies on the actual consequences from natural hazards on the spreading of pollutants. It would be possible to use the same approach for other natural hazards than landslides. Such approach could also include all possible natural hazards and the probability that environmental quality standards or other criteria will be exceeded if any of the hazards occurs. This part has not been done yet, thus this paper will only present the suggested approach and a first, very simplified, conceptualization.

3 RESULTS

3.1 Quick scan method for hazard identification at a river basin scale

The identification of contaminated sites vulnerability to natural hazards, and at a river basin scale, is done by superimposing the contaminated land objects with each of the base support mentioned in Table 1. The base support is grouped into four categories: *i)* landslides, *ii)* debris flows, *iii)* bank erosion and, *iv)* flooding.

In our study we chose to display the contaminated sites by a colour-coded star (the colour depends on the environmental risk classification) and a colour-coded square that tells what type of natural hazard the object is vulnerable to. The municipality of Hallstahammar was used as a case study to test the method. Figure 1 displays an example of how the results of the identification can be presented on map. The identified contaminated sites represent concrete and cement industry, dry cleaning, ship yard, saw mill, pulp mill, landfill, etc.

3.2 Quick scan method for vulnerability assessment of a single object

For illustration, we have used the Block Hake in the town Köping, Sweden. The site is located adjacent to Köpingån river and Kölstaån river. Figure 2 shows block Hake marked on an aerial photo. Previous investigations include environmental investigations, a general slope stability

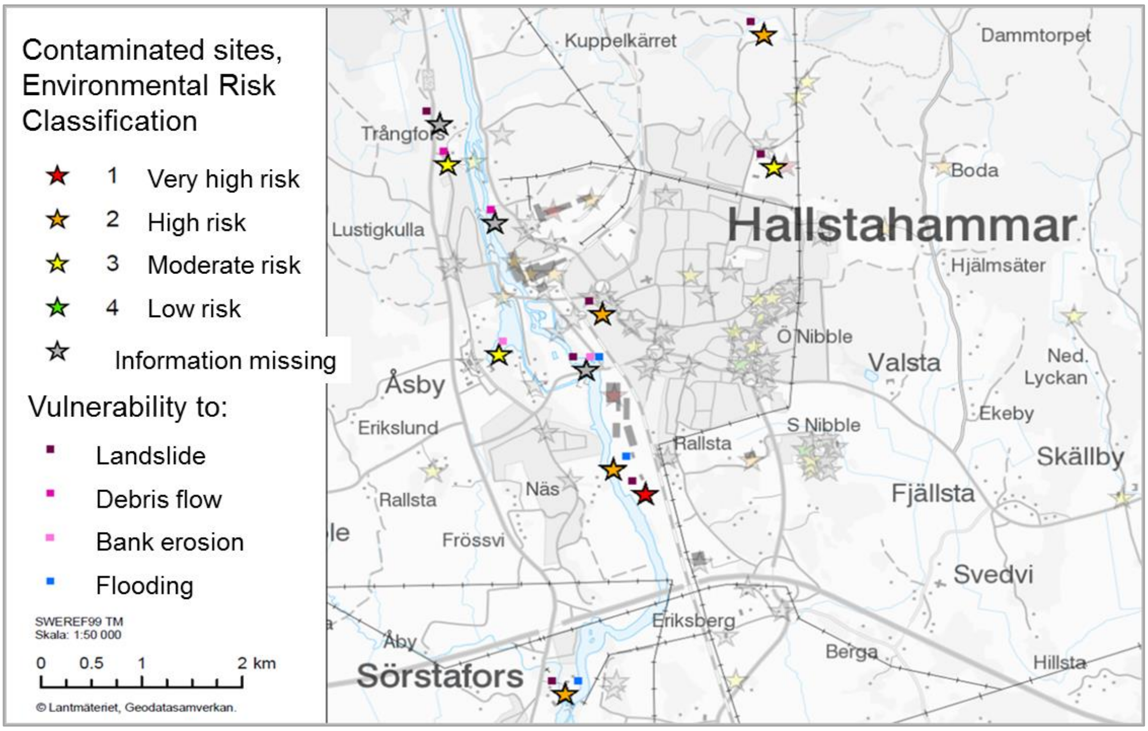

Figure 1. Example of how the results from the hazard identification can be presented on map (here, part of Hallstahammar municipality). All stars are identified as potentially contaminated sites. The highlighted stars are the one with identified vulnerability to landslide, debris flow, bank erosion and/or flooding. © SGI, Lantmäteriet, Geodatasamverkan.

zonation map, a general inventory of erosion conditions, a general flood risk map, and a climate analysis for the County Administrative Board.The site has previously been assessed with a high environmental risk classification (environmental risk class 2). The soil contains both organic and inorganic contaminants. A summary of the results from the existing data on slope stability, erosion, flooding and increased precipitation:

- The general slope stability zonation map shows that the area is situated within a zone that indicates unsatisfactory stability and that detailed investigations are needed.
- The bank material consists of flood plain deposits and there are indications of active erosion.
- According to a flood risk map (not updated for climate change effects), the site is located within an area that will be flooded only during a theoretically calculated maximum flow. However, a thin strip along the shoreline is within the marked area for 100-year flood. The climate analysis for the county shows that future 100-year flood will slightly decline.

The climate analysis for the county indicates that annual precipitation will increase by 20% until 2100 with a major increase during winter. The rain intensity will also increase.

Figure 2. Aerial photo that shows case study site Block Hake with the rivers Köpingån and Kölstaån. ©2015 Google Image, ©Lantmäteriet/Metria.

In the summary matrix, a mark (cross) or a text is inserted in relevant box for each identified and vulnerability assessed hazard to aid decisions on further investigations/actions (Table 7).

Table 7. Identification and general assessment of the contaminated site's vulnerability to natural hazards and assessment of the need for additional investigation. The soil is contaminated with high to very high concentrations of PAHs, copper, lead and zinc.

Vulnerability to natural hazards	**Negligible vulnerability**	**Minor vulnerability**	**Moderate vulnerability**	**Major vulnerability**
Soil movement				Not satisfactory stable according to the general slope stability zonation map
Bank erosion			Flood plain deposits, < 100 m to beach, active erosion, partly covered by erosion protection.	
Flooding		Within CMF marked area, only a limited stretch within Q_{100}, active erosion but partly protected from erosion.		
Change in precipitation				Approx. 20% increase in mean annual precipitation, but also increase of heavy rainfall.
Investigation need	No further investigation is needed.	The area cannot be disclaimed from flooding, monitoring is necessary.	Need for further risk assessment regarding erosion, probable need for action.	Urgent need for in-depth risk assessment regarding landslide risk and precipitation increase, action needed.

With respect to the overall analysis, the preliminary assessment is that the contaminated site has major vulnerability to increased spreading of contaminants from landslide and increased precipitation. Also bank erosion may contribute to the spreading of contaminants. The site is hence in need of more detailed investigations and action with respect to slope stability and climate change effects.

3.3 Proposed method for risk estimation of a single object

The approach to estimate possible environmental consequences from contaminated land exposed to natural hazards include three major parts:

1. To set up a conceptual model that describes governing processes for mobilisation of contaminants from natural hazards and that identifies and characterizes impact zones for possible consequences.
2. To define failure criteria for each of the identified impact zones, decide models to calculate probabilities of failures and to set parameter values and parameter uncertainties into these models.
3. Compute the probability of failure for all identified failures and perform a sensitivity analysis of the results to analyse which probability/-ies that governs failure in order to find cost effective measures.

A first and simplified conceptualization is shown in Fig. 3 and that roughly illustrates a contaminated site and how natural hazards may impact the further spreading of pollutants. In anticipation of more knowledge about real consequences, concentration above Predicted No Effect Concentrations (PNEC) for each contaminant is suggested as criteria for failure. A preliminary and general definition of failure is suggested as the probability that any/all of possible natural hazards may cause an increase of contaminants in, for example, the water body above PNEC. This can be written as:

$$P_f = P_L \times P_E \times P_F \times P_{IP} \times P[C_w > PNEC] \quad (1)$$

Where P is the probability, P_f is the probability for failure, P_L is the probability of landslide, P_E is the probability of erosion, P_F is the probability of flooding, P_{IP} is the probability of increased precipitation, C_w is the concentration in the water body. The probabilities should include climate scenarios for futureThe next step in our study will be to identify possible impact zones in the near field and far field, with respect to ecosystems and humans, and to conceptualize the governing pathways. The general definition of failure must then be refined to describe possible failures in each of the impact zones, and models to calculate probabilities will be developed.

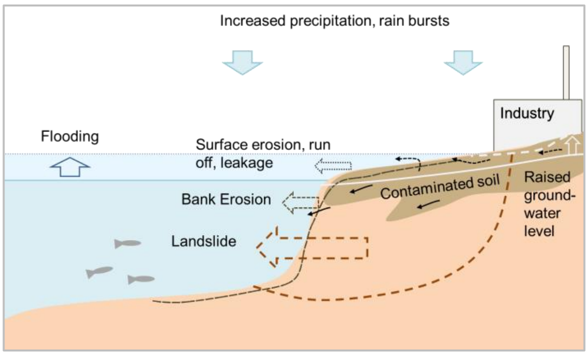

Figure 3. A simplified coneptualization of contaminated land exposed to natural hazards.

4 DISCUSSION

It should be mentioned that the approach presented in this paper is not meant to stand alone for a full risk analysis but is meant to be a complement to existing methods for risk assessments.

The study shows the possibility of using GIS information to identify multi-hazards that otherwise would not have been revealed. By applying one of the quick scan methods an estimation of whether there is vulnerability to natural hazards in contaminated areas can easily be done and decisions on prioritization on detailed investigation and risk assessment can be taken. The quick scan methods will be fully described in a SGI Publication that at the moment is out for review by a number of municipalities, county councils, the Swedish EPA, the Swedish Civil Contingencies Agency, and others. There is a need for instructions for detailed risk assessment and actions with respect to contaminated sites and natural hazards and how that can be included in already existing methods for risk analysis.

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