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A methodology for estimating risks associated with landslides of contaminated soil into rivers

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HIGHLIGHTS

- Risks associated with contaminant spreading from landslides into rivers are analysed.
- A probabilistic methodology to estimate the risks is developed and tested.
- Given a landslide, the probability of exceeding environmental quality standards is high.
- The methodology developed is a complement to existing risk assessment methods.

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ABSTRACT

Urban areas adjacent to surface water are exposed to soil movements such as erosion and slope failures (landslides). A landslide is a potential mechanism for mobilisation and spreading of pollutants. This mechanism is in general not included in environmental risk assessments for contaminated sites, and the consequences associated with contamination in the soil are typically not considered in landslide risk assessments. This study suggests a methodology to estimate the environmental risks associated with landslides in contaminated sites adjacent to rivers. The methodology is probabilistic and allows for datasets with large uncertainties and the use of expert judgements, providing quantitative estimates of probabilities for defined failures. The approach is illustrated by a case study along the river Göta Älv, Sweden, where failures are defined and probabilities for those failures are estimated. Failures are defined from a pollution perspective and in terms of exceeding environmental quality standards (EQSs) and acceptable contaminant loads. Models are then suggested to estimate probabilities of these failures. A landslide analysis is carried out to assess landslide probabilities based on data from a recent landslide risk classification study along the river Göta Älv. The suggested methodology is meant to be a supplement to either landslide risk assessment (LRA) or environmental risk assessment (ERA), providing quantitative estimates of the risks associated with landslide in contaminated sites. The proposed methodology can also act as a basis for communication and discussion, thereby contributing to intersectoral management solutions. From the case study it was found that the defined failures are governed primarily by the probability of a landslide occurring. The overall probabilities for failure are low; however, if a landslide occurs the probabilities of exceeding EQS are high and the probability of having at least a 10% increase in the contamination load within one year is also high.

1. Introduction

Contaminated land subject to landslides poses a risk for mobilisation and spreading of contaminants into rivers, as has previously been highlighted in papers by Göransson et al. (2009; 2012). The first paper identified the combination of landslides and contaminated land as a multi-risk and suggested a conceptual model for the governing processes. The second paper applied a one-dimensional advection–dispersion equation for the description of possible sediment, and subsequent contaminant transport for the instantaneous release of contaminants from landslides.

Landslides are often natural geomorphological processes resulting from nature striving towards equilibrium and they are important for the rejuvenation of the ecology (Geertsema et al., 2009). In pristine environments such events release nutritious sediments to the surroundings and are mechanisms for maintaining aquatic and terrestrial biodiversity and heterogeneity (Attiwill, 1994; Geertsema and Pojar, 2007). A landslide can cause an instantaneous increase in turbidity,

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which influences light suppression, and it may induce a sudden change in redox and pH, or cause instantaneous fish kill because of the physical chock. Such impacts only remain for a limited period of time and most natural systems are resilient to these events and have capacity for recovery (Folke et al., 2004; Holling, 1973; Waples et al., 2009).

However, when a natural system is no longer pristine but transformed into an anthropogenic system, a landslide may not only be triggered by human activities but the consequences may also increase because anthropogenic systems are often contaminated to various extents. For example, release of excessive nutrients from agriculture or bacteria and viruses from pasture lands into rivers from landslides (Ohlson and Serveiss, 2007) and landslides that involve contaminated material can transport pollutants from land to rivers. This can occur either directly due to the sliding masses or indirectly by flooding and bank erosion of polluted areas as a consequence of damming and landslide generated impulse waves (Göransson et al., 2009, 2012; Bonnard et al., 2004). A landslide that involves the release and transport of contaminating substances may also trigger a shift into an ecosystem of less resilience (Folke et al., 2004; Holling, 1973; Walker et al., 2009).

Although urban areas and industrial sites are commonly located adjacent to surface water, very few studies have paid attention to the risk for mobilisation and spreading of pollutants to surface waters due to landslides (Göransson et al., 2012). Existing methods for environmental risk assessment (ERA) and risk management at a river basin scale do not provide information on the possible environmental impact from landslides or other types of mass movement. Yet fine sediment, sediment transport, as well as contaminant transport and mobilisation due to groundwater flow and the release of contaminated sediments from rivers and floodplains due to flooding are typically mentioned in ERA (see for example Landis, 2004; Marcus et al., 2001; US EPA, 2012; and European projects like RISKBASE, MODELKEY, AguaTerra; e.g., Diaz-Cruz et al., 2007; Finkel et al., 2010; or visit www.riskbase.info, www.modelkey.org). In addition, existing methods for landslide risk assessments (LRA) do not account for the pollution potential although the environment is often included as an element at risk (see for example Li et al., 2010; Ohlson and Serveiss, 2007; Serveiss and Ohlson, 2007; Poli and Sterlacchini, 2007; Sterlacchini et al., 2007; or visit the European project SafeLand at www.safeland-fp7.eu).

The risk of landslides in polluted areas is increasingly relevant since there are indications that: (1) landslide frequencies may increase in areas with increasing precipitation or temperature (although the uncertainties still remain high) and (2) there is a possible increase in anthropogenic landslides due to unsustainable development (Borgatti and Soldati, 2010; Crozier, 2010; Jakob and Lambert, 2009; Kuriakose et al., 2009; Klimeš and Novotný, 2011; Larsen, 2008; Listo and Vieira, 2012; Ren et al., 2011). It is therefore relevant to develop an approach for assessing the risks associated with contaminant mobilisation from landslides in order to include this issue into risk models.

The main aim of this study is to propose a methodology for quantitative estimation of risks to water bodies from landslides involving contaminated land. Risk is here related to the probability of exceeding a defined failure criterion, whereby the consequences associated with the event of interest can not necessarily be quantified. The suggested methodology may be a useful complement to ERA at contaminated sites or in LRA, or provide important input in river basin management. The suggested methodology is illustrated through a case study.

2. Conceptualisation

The governing processes for the release and exposure of contaminants from landslides have been described in Göransson et al. (2009; 2012). Based on these two studies, the conceptualisation of the contaminant release and exposure mechanisms is as follows:

A. An instantaneous exposure in the near field as the contaminated masses come into contact with the water because of the slide.
B. An instantaneous release of particle bound contaminants from the landslide deposit as it reaches the surface water and soil particles go into suspension. Particle bound contaminants are mobilised and further transported downstream (upstream transport is also possible) with the landslide-generated wave and the river flow. Exposure along the downstream transport pathway is possible as the contaminant pulse moves down the river.
C. An instantaneous release of dissolved substances from the landslide deposit as the contaminated masses reach the water column and are transported with the flow. Exposure along the downstream transport pathway with the water flow is possible.
D. More or less instantaneous exposure in the accumulation area (far field) when the released substances settle.
E. A long-term exposure in the near field from the contaminated landslide deposits. Releases of both particle and dissolved contaminants from the runout are expected as a consequence of erosion and diffusion. Such releases can continue for a very long time (years, decades), if dredging does not take place. Possible long-term exposure along the pathway depends, for example, on dispersion processes.
F. A long-term exposure in the far field is expected as contaminants accumulate from the event.

Given the conceptualisation above, potential consequences can be related to three impact zones: I) the near field, II) along the transport pathway, and III) the far field accumulation area; see Fig. 1 and Table 1. Zone II may be limited when the slope runs out directly into a lake or the sea.

3. Suggested risk estimation methodology

The common definition of risk includes the combination of the probability of an event and the undesirable consequences of such an event. Typically, a risk assessment starts with hazard identification. Here, the hazard is already defined as the combination of slope instability and land contamination; thus, the identification step is not included in the suggested methodology but is described in Göransson et al. (2009).

There are no studies on environmental consequences for the impact zones described above and the consequences must therefore be defined from something other than field measurements or experiments, for example from a policy or acceptance aspect. The suggestion made here is to use environmental quality standards (EQS) since they indirectly tell something about the risk because they consider effects (e.g., biological) and responses (e.g., the amount affected). Accordingly, the methodology does not describe the consequences but is based on the identification of failures. These failures are defined in terms of exceeding relevant guideline or threshold values related to contaminant concentration or maximum additional contaminant load to the system. Failure criteria are defined for each of the impact zones (I–III) and a decision is then made on the probability models to use for the calculation of these failures. For each case, one needs to investigate data availability, find expert judgements when data are lacking and consider the uncertainties in the data and the judgements. The risk is then estimated by calculating the probability of failure in each impact zone. The following working approach is suggested and further explained under the coming sections:

1. Identify initial conditions of the surface water system.
2. Define failure for impact zones I–III.
3. Decide models to calculate probabilities of failure.
4. Set parameter values and parameter uncertainties.
5. Compute the probability of failure (P_f) for all identified failures.
6. Perform a sensitivity analysis.

The work is preferably carried out in an iterative mode, since the level of complexity of the analysis depends on what the result will be used for and on the available resources in the form of data, knowledge, and funding.