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Mass transport of contaminated soil released into surface water by landslides (Göta River, SW Sweden)

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Abstract

Landslides of contaminated soil into surface water represent an overlooked exposure pathway that has not been addressed properly in existing risk analysis for landslide hazard, contaminated land, or river basin management. A landslide of contaminated soil into surface water implies an instantaneous exposure of the water to the contaminated soil, dramatically changing the prerequisites for the mobilisation and transport of pollutants. In this study, an analytical approach is taken to simulate the transport of suspended matter released in connection with landslides into rivers. Different analytical solutions to the advection-dispersion equation (ADE) were tested against the measured data from the shallow rotational, retrogressive landslide in clayey sediments that took place in 1993 on the Göta River, SW Sweden. The landslide encompassed three distinct events, namely an initial submerged slide, followed by a main slide, and a retrogressive slide. These slides generated three distinct and non-Gaussian peaks in the online turbidity recordings at the freshwater intake downstream the slide area. To our knowledge, this registration of the impact in a river of the sediment release from a landslide is one of the few of its kind in the world, and unique for Sweden considering the low frequency of landslide events, making it highly useful for evaluating how appropriate the ADE is to describe a landslide into surface water. The results yielded realistic predictions of the measured concentration variation, after proper calibration. For the three individual slides it was estimated that a total of about 0.6 % (515 000 kg) of the total landslide mass went into suspension/was suspended and was transported downstream. This release corresponds to about 1 to 2 % of the annual suspended sediment delivery for that river stretch. The studied landslide partly involved an industrial area and by applying the analytical solution for the transport of metals in the sediments it was found that landslides have the possibility to release a significant amount of pollutants if large contaminated areas are involved. However, further studies are needed to develop more detailed descriptions of the transport processes. There is also a need to increase the knowledge on possible environmental consequences in the near and far

field, in a short and long-time perspective. Finally, the risk for the release of pollutants should not be neglected in landslide hazard and risk assessment.

1 Introduction

In landslide risk analyses, most methodologies emphasize geomorphologic, social, or economic aspects of the phenomenon rather than the ecological impact in receiving waters, and only a few studies have been undertaken to understand the impact on water quality from the mass movement. Mass movement causes physical disturbance, redistribution of sediments and an increase in suspended matter, which affect both the physical environment and the ecology. Anthropogenic substances that accumulate in sediments are nutrients, heavy metals, and organic pollutants. The pollutants may occur dissolved, free or in complexes, or associated with the particulates either adsorbed or precipitated. From a risk perspective, the possible shifts between different states and species have large implications. Such shifts towards dissolved species imply significant impact due to their higher bioavailability (Goossens and Zwolsman, 1996).

There are a few studies on bank erosion as a source of pollution but they are in general rare (Caruso, 2001). Some investigations have indicated the pollution of rivers and lakes from peat or bog flows and from bank erosion during flooding (Dykes and Warburton, 2008; Daniels et al., 2008; Thoma et al., 2005; Ciszewski, 2001). In a study by McCahon (1987), an effort was made to back-calculate the impact on water quality from a peat slide that caused fish kill. It was demonstrated that the slide caused considerable change in water chemistry with large increases in the concentration of suspended solids and metals.

Mass movement (e.g. landslides, debris flow, bank erosion) can supply large amounts of sediment to surface waters, representing a major sediment source in a catchment (Mouri et al., 2011; WARMICE, 2003). There are several recent studies on the sediment delivery from landslides, their contribution to the sediment flux and erosion of the displaced toe (see for example Mackey and Roering, 2011; Schwab et al., 2008; Bayer and Linneman, 2011; Ono et al., 2011). In river basin management, the understanding of sediment discharge on a catchment scale is of major importance. In general, sediment discharge can be divided into stream channel sediment transport (bed load, suspended load, and wash load) and land surface transport (mass movement) (Mouri et al., 2011). These two transport pathways are associated with different time scales, where the transport on a sloping land surface is rapid compared to that in a stream channel (Mouri et al., 2011). Mouri et al. (2011) modelled such a system by combining a slope model with a stream channel model. Further, the sediment transport from a landslide containing contaminated soil into surface water can be divided into (Göransson et al., 2009): (i) an instantaneous release of sediment followed by, (ii) a long-term release. The instantaneous release of sediment represents the phase when the soil mass moves into the water. The mobilisation of sediment by the landslide and the associated water motion generates a large amount of suspended particulate matter (SPM), initiating the transport of a sediment pulse and associated contaminants. When the concentration of suspended material reaches the critical transport capacity of the water body, material starts to settle. This course of event is rapid and intense and the contaminants are mobilized instantaneously with the SPM. The long-term release and associated impact over longer distances occurs when the hydraulic regime returns to normal conditions and the SPM settles in the far field. Long-term release of contaminants takes place through erosion of the run-out during high-flow events in the areas where sediment from the SPM pulse has settled.

The objectives of this study are threefold:

1. To identify the main mechanisms determining the evolution of the SPM concentration after a landslide into surface water based on field observations from Göta River, SW Sweden.

2. To model the evolution of the SPM concentration using analytical solutions to the advection-dispersion equation and assess the usefulness of such solutions.

3. To estimate the contribution of the SPM transport from the landslide to the sediment budget and pollution load from the river.

The assumption is made that the traditional advection-dispersion equation (ADE) in one dimension (1-D) for a slug injection, coupled with appropriate source/sink terms under given initial and boundary conditions, is appropriate to describe the initial transport of SPM released through the landslide. The mass movement into the river is assumed to be a very fast process compared to the retention time of the river, implying instantaneous and uniform mixing across the river.

A landslide occurred along the Göta River in 1993 in the municipality of Agnesberg, located just north of Gothenburg city, Sweden. Detailed turbidity measurements were carried out at a freshwater intake about 2.6 km downstream the landslide area. These data were used to evaluate the ADE for describing the transport of SPM. The landslide was a rather small slide, mainly consisting of clay that is highly sensitive to disturbances, partly involving an industrial site. The observed turbidity time series, which was converted into SPM concentrations based on a calibration relationship derived using field samples, is unique in its kind and no other registration of the variation in SPM concentration due to a landslide is known to the authors. The recorded pulses show a skewed, non-Gaussian form in time, with a steep and quick rising limb followed by a slower falling limb and a long tail.

2 Landslides into surface waters

2.1 Mass movement

Mass movement of contaminated soil into surface water encompasses both physical and chemical processes and is an interdisciplinary research area. The stability of a slope (e.g. hillside or riverbank) is governed by the balance between resisting and driving forces. When the driving forces exceed the resisting forces by cohesion and friction between soil particles, the soil starts to move (Lambe and Whitman, 1979). As the contact between particles diminish, and as the moving soil mass becomes liquefied (a slurry), particles come into suspension and are no longer attached to each other (Ter-Stepanian, 2000). The effective stresses between particles is reduced and the forces act through the fluid instead (Ter-Stepanian, 2000). As the soil mass moves into a surface water (a river, lake, or coastal area), it causes instantaneous hydraulic changes and generates surface gravity waves, through the impulse generated by the soil mass impacting the water (Heller, 2008).

Göransson et al. (2009) presented a first description and overview of the processes involved in the mobilisation and spreading of contaminants from landslides into surface waters (Fig. 1). The movement of the soil, as well as cracking, stirring, and mixing, changes the prerequisites for the mobilisation of contaminants due to changes in redox potential, pH, and water content. As the run-out reaches the surface water and the impulse wave is generated (that may have large impact on riverbanks during its path), particles from the run-out deposits come into suspension. The SPM released will most likely be travelling downstream through a pulse, as was observed for the Agnesberg landslide, and so will associated pollutants. When sediment concentration exceeds the transport capacity of the river, the particles will start to settle.

2.2 Water quality impact

There are only a limited number of studies on mass movements and the impact on water quality of which a few is summarised in the following text. In the Sumas River, near the US-Canada border, a slow-moving and active landslide in the headwaters of the stream releases up to ca 90 000 m^3 of excess sediment each year, which is carried downstream by Swift Creek (USEPA, 2011). These sediments contain naturally occurring asbestos (thin fibrous from silicate minerals). Running water from the Sumas Mountain picks up asbestos-containing rocks and soil in the landslide and carries them downstream (USEPA, 2011). The landslide derived sediments cause extreme sedimentation in the Swift creek (Bayer and Linneman, 2011) and it was found that the asbestos fibres in the stream sediment are dispersed seasonally in relation to the discharge and that there is a downstream movement of these asbestos materials over time (Schreier, 1987). In 1990, a landslide took place in the Surma Khola Valley, the High Mountain Region of the Central Nepalese Himalaya, that increased the suspended sediment concentration in the Surma Khola river by approximately 50 times for a short period of time (Reis, 2000). It took about three days for the sediment pulse to pass one of their gauging station; however, the discharge decreased much more slowly (Reis, 2000). During that time the calculated suspended sediment transport increased by three orders of magnitude, from 62 g s^{-1} to 23 kg s^{-1}. It was calculated that the specific suspension delivery during these days reached twice the annual delivery (Reis, 2000). In a thesis by Rhoades (2008), mercury contamination from bank erosion was estimated for the South River, Virginia, USA. Leakage of mercury from industrial activities in the past had contaminated riverbank sediments. The concentration ranged from 5 to 140 ppm and contaminated sediments were delivered to the river channel through bank erosion. It was estimated that a minimum of 161 000 m^3 of sediment eroded from the bank each year, releasing about 110 kg of Hg per year (Rhoades, 2008).

A study on Swedish mass movement events, mainly rotational and translational earth slides, earth falls, and debris falls, revealed that out of 42 studied events, contaminant mobilisation could be suspected in 15 of these events (Åkesson, 2010). In the same study, hydrodynamic observations were made and it was found that surging (17 of these events), damming effects (29 events), and a vast increase in suspended matter (14 events) were common consequences. One slide documented in the study is the Yara landslide in 2007, which was an earth slide that occurred within an industrial area (earlier producing and today distributing mineral fertilizers). The slide transported about 1200 m^2 landfill material and partially contaminated clays into Ståthöga bay near the city of Norrköping, SE Sweden. As a result, a new bay was formed at the site of failure, exposing contaminated mass estimated to contain 300 to 500 kg arsenic, 600 to 1000 kg lead and zinc, and 200 to 400 kg copper to the neighbouring surface waters (Persson, 2007).

The Tångböle slide in 1995, adjacent to the Indal River, Sweden, caused an instantaneous and more than six-fold increase in sedimentation in the nearby Lake Gevsjön. Signs of pollution were noted and local supply and usage of freshwater were restricted. The 1957 Göta earth slide in Göta River, SW Sweden, displaced 300 000 to 450 000 m^2 of land and took place within a pulp-mill industrial site. In this accident three men died and several more were injured. The material damage was extensive and large amounts of plausibly contaminated scree lay uncovered and exposed to both wind and water.

2.3 Suspended sediment transport and distribution

Some distance away from the release point, the SPM is assumed to be fully mixed and the concentration uniform over any cross-section. Spatially, the concentration only varies along the river. According to theory, the sediment concentration will then follow a normal distribution in space that propagates downstream with the mean velocity. The dispersion of SPM is mathematically described by Fick's law in the ADE. The dispersion coefficient will include the combined effects of molecular diffusion, turbulent mixing, and mixing due to transverse and vertical shear associated with cross-stream velocity differences (Singh and Beck, 2003). However, results from field experiments and observations in natural channels have shown that a suspended sediment, colloid, or dissolved element pulse does not always form a normal distribution, but frequently a skewed distribution with a sharp front and long tail occurs (Jobson, 2001). This phenomenon is commonly referred to as non-Fickian dispersion and may be a result of one of, or a combination of, the following mechanisms: (i) complete hydrodynamic mixing is not fully reached at the point of observation, (ii) a reversible or irreversible exchange occurs with stagnant or slowly moving water masses ("dead zones"), porous streambeds, hyporheic zones, and viscous sub layers, and (iii) biogeochemical reactions, such as sorption, dissolution/precipitation, and decay/production take place.

Davis et al. (2000) noted that empirical observations in natural channels often does not support the assumption that a skewed concentration distribution eventually will converge to a symmetric distribution that fulfils the ordinary 1-D ADE. However, measurements are often taken in time at a specific point in space, and if the dispersion is large the spreading of the concentration distribution as it passes the measurement point will give the distribution a skewed shape in time.

In order to describe non-Gaussian behaviour in the SPM concentration, so-called "dead zone models", that is reversible (transient) or irreversible storage in stagnant domains, have been used by for example Atkinson and Davis (2000), Chanson (2004), Karwan and Saiers (2009) and Singh and Beck (2003). Such behaviour may also be a consequence of non-fulfilment of the initial conditions and the assumption of uniform concentration across the river cross section (Singh and Beck, 2003). In addition, entrapment of material on shelf-type banks along the river side with low velocity near the bed and banks (i.e. dead zones) probably contributes to departure from the theoretical solution (Singh and Beck, 2003; Davis et al., 2000). An approach to achieve a more asymmetric shape on the SPM concentration is to add an empirical skewness coefficient to the ADE (van Mazijk and Veling, 2005), or a shape parameter in the case of a flood wave pulse (Bender et al., 2011). Deng et al. (2001, 2002) highlighted the influence from meandering and non-uniform conditions of rivers and the importance of the transverse velocity profile and depth to the production of longitudinal dispersion. They considered this by deriving a channel shape equation, arriving at a triple integral expression for the longitudinal dispersion coefficient. Subsequently, Deng et al. (2011) and Deng and Jung (2009) introduced a variable residence time (VART) model that includes transient storage and hyporheic exchange. They found that mainly three parameters govern the solute exchange between surface stream water and subsurface sediment pore water, namely the area of advection-dominated transient storage zone divided by cross-sectional flow area of the main channel, the effective diffusion coefficient in a hyporheic zone divided by cross-sectional flow area of the main channel, and the minimum mean residence time for solute to travel through the advection-dominated storage zone. In small streams, the dispersion term is negligible compared to the transient storage. The VART model generates different tail behaviour of the residence time distribution due to advection and effective diffusion processes, implying that the hyporheic exchange has large impact on the transport processes in small streams (Deng et al., 2010).

3 Study area

3.1 Göta River

The Göta River stretches from Lake Vänern to the outlet at the city of Gothenburg (Fig. 2). The mean flow is about 565 $m^3 s^{-1}$ (SMHI, 2008). South of Kungälv, the river divides into two branches around a large island; the northern branch (i.e. the Nordre River) receives on the average 2/3 of the total discharge, whereas the remaining discharge goes through the southern branch (still referred to as Göta River) (GÄVVF, 2006). The river flow is regulated by three hydropower stations located upstream the branching. The river stretch is quite straight with only a few meanders and has a mean width of 500 m before the branching and of 100 m in the southern branch. The main channel has typical depths of 7–10 m with deeper local cavities. The channel margin forms in most cases a distinct bank shelf. River sediments consist mainly of thick layers of glacial and post-glacial cohesive sediments with thin layers of silt and sand. The areas surrounding the river are pasture lands, forests, bedrock, and small urban industrial areas. Almost no sedimentation occurs in the river and the transport of suspended particles (purely inorganic) has been estimated to about 130 000 t yr^{-1}, of which 50 000 t yr^{-1} are transported through the southern branch (Sundborg and Norrman, 1963). Göransson et al. (2011) estimated the annual suspended sediment transport in the southern branch to about 30 000 t.

3.2 Landslides

The areas along Göta River have the largest landslide frequencies in Sweden. Most of the slides have been classified as rotational earth slides and due to the occurrence of so-called quick clay some slides have propagated to encompass huge areas. Along the 93 km stretch from Lake Vänern and through the southern branch of the river, more than 60 slides have been documented over time, the first one in a church book from mid 1150. At least 16 of these slides involved large areas (up to ∼500 ha) (SGI, 2011). Partial or full damming of the river, landslide-generated waves and increase in water turbidity are some documented effects in connection with landslides. The most recent events involved a municipality (Surte landslide, 1950), a pulp-mill factory (Göta landslide, 1957) and an industrial site (Agnesberg landslide, 1993). The risk for the spreading of pollutions from contaminated soil was only mentioned in a few of the landslides, but no measurements were ever carried out to analyse possible environmental consequences. There are several industrial areas adjacent to the river where a significant risk for landslides exist (Göransson et al., 2009).

3.3 Water quality

Several stretches of the Göta River, some tributaries to the river, and the estuary of Nordre River, are protected under the European Natura 2000 network (centrepiece of EU Nature & Biodiversity Policy). The river serves as an important waterway to and from harbours along the river and around Lake Vänern. The river is both the recipient of treated wastewater and the drinking water supply for 700 000 inhabitants in Gothenburg city. There was significant deterioration of the water quality in the 1970s, but the installation of advanced wastewater treatment plants yielded considerable improvement to the water quality. Today, nutrients and microorganisms from the wastewater treatment plant remain a threat to health and environment.

The water quality in the river is primarily affected by direct runoff from urban, rural, and livestock areas, treated wastewater from urban areas, combined sewer overflow during heavy rainfall (Åström et al., 2007), leakage from contaminated sites, and accidental spills from industries and vessels. The water quality is to a large extent influenced by the outflow from Lake Vänern into the river (GÄVVF, 2006). Turbidity (as well as pH, redox, and conductivity) is continuously recorded at seven gauging station along the river, with the purpose of providing an early warning in case of reduced water quality. The most downstream gauging station is located at the freshwater intake (Lärjeholm; see Fig. 2). In general, the intake is closed about 100 days a year during which freshwater is taken from a system of reservoirs. If the water quality deviates from normal conditions, additional sampling will start automatically.

4 Model of concentration variation in a river due to sediment release from landslides

4.1 Advection-dispersion equation (ADE)

Traditionally, the advection-dispersion equation (ADE) (see Fisher et al., 1979) has been used to model the concentration in rivers and how it evolves in time and space due to a pollution release. In a river, a reasonable simplification is to employ a one-dimensional approach in space, assuming that all quantities in the ADE can be adequately represented by their cross-sectional averages. Such averaging implies that the dispersion coefficient, which characterizes the longitudinal mixing, not only includes the diffusive processes but the effects of the cross-sectional variation in velocity as well. As a first approximation, the ADE will be used in the present study to describe the effects of a landslide on the concentration of suspended material in a river. It will be assumed that most of the material released into the river during a landslide will be transported in suspension and coarser material that may move as bed load is not taken into account. Karwan and Saiers (2009) employed a similar equation to model particle movement in a stream, where the deposition was quantified through a coefficient corresponding to w/h (settling velocity over water depth). Furthermore, a second equation was used to describe the transient storage (compare Atkinson and Davis, 2000).

The one-dimensional ADE with a sink term (sediment deposition) for the suspended sediment transport in a river may be written,

$$\frac{\partial c}{\partial t} + U\frac{\partial c}{\partial x} = D\frac{\partial^2 c}{\partial x^2} - \frac{wc}{h} \tag{1}$$

where c is the concentration (mass per unit volume), U the mean velocity in the river, D the dispersion coefficient, w the settling velocity, h the water depth, x the spatial coordinate along the river, and t the time. The equation describes how sediment is transported downstream with the mean velocity (advection), at the same time being subject to mixing (dispersion) and settling at the bottom. The settling is quantified by the last term on the right-hand-side of Eq. (1) that acts as a sink for the sediment. No attempt is made to describe the mobilization of sediment (pick-up) from the bed, but it will be assumed that the sediment transported by the river is supplied from the landslide only, through an instantaneous pulse (mathematically described through a Dirac delta function) at some specific location.

The ADE may be solved analytically for a wide range of problems where the initial, boundary, and forcing conditions are sufficiently simple. However, for applications to a more complex situation, which is typically the case in practical studies in natural rivers, the ADE must be solved numerically, for which many different techniques are available (Vreugdenhil and Koren, 1993). In the present study, however, an analytical approach will be taken to investigate whether the ADE can reproduce the observed variation in SPM concentration in a river as a result of a landslide. If an analytical solution to the ADE can capture the main features of the variation in SPM, then certain characteristic quantities such as the maximum concentration, time to peak, and duration of the event may be predicted in the case of a landslide occurring upstream a certain location. Furthermore, analytical solutions to the ADE may be efficient to use for general risk assessment when a large number of alternatives and their potential impact needs to be determined.

4.2 Analytical solution to the ADE

The solution to Eq. (1) for the case of a release of the sediment mass M (kg) instantaneously at $x = 0$ and $t = 0$ is given by (Carslaw and Jaeger, 1959),

$$c(x,t) = \frac{M}{A\sqrt{4\pi Dt}} \exp\left(-\frac{(x-Ut)^2}{4Dt} - \frac{wt}{h} \right) \quad (2)$$

where A is the cross-sectional area of the river. This equation represents a concentration distribution that follows a Gaussian shape in space at any given time, where the centreline of the distribution moves downstream with the velocity U (if $U > 0$, otherwise the distribution moves upstream). Simultaneously with this advection, the distribution is spreading symmetrically around the maximum value because of dispersion. If $w = 0$, the Gaussian shape contains the same mass of material at all times ($= M$), but if $w > 0$ then the mass in the water is decreasing. The solution given by Eq. (2) assumes that the river and sediment properties (i.e. A, D, U, h, and w) are constants, not changing with space or time. Analytical solutions to ADE for other initial and boundary conditions may be found in Carslaw and Jaeger (1956) and Crank (1975).

In general, with due regard to the boundary and initial conditions, it is possible to derive new solutions simply by superimposing existing solutions since the governing differential equation (Eq. 1) is linear for constant coefficients. Thus, if a landslide contains two main fractions of material with different settling velocities, the transport of these fractions could be modelled separately with Eq. (2) and the solutions then added together to obtain the total concentration of SPM, if there is negligible interaction between the two fractions when they are transported. Also, a more complex release of material from a landslide, taking into account the time history of how the material was released to the river and not regarding it as an instantaneous source, may be described through the superposition of a large number of instantaneous sources of proper magnitude and location in time.

Rewriting Eq. (2) in terms of a constant mass transport rate m (unit kg s^{-1}) at time t_s during a short period Δt yields the following solution,

$$c(x,t) = \frac{m\Delta t}{A\sqrt{4\pi D(t-t_s)}} \exp\left(-\frac{(x-U(t-t_s))^2}{4D(t-t_s)} - \frac{w(t-t_s)}{h}\right) \tag{3}$$

which is valid for $t > t_s$. Thus, a landslide event, assumed to be made up of a large number of such short events, where the sum of all small releases m will yield M, produces the following solution (Larson et al., 1987):

$$c(x,t) = \frac{1}{A\sqrt{4\pi D}} \int_0^t m(t') \frac{\exp\left(-\frac{(x-U(t-t'))^2}{4D(t-t')} - \frac{w(t-t')}{h}\right)}{\sqrt{t-t'}} dt' \tag{4}$$

where $m(t')$ is a function describing the time history of material release from the landslide and t' is a dummy integration variable. A possible description of how the material release occurs during a landslide, including the initial mixing over the river cross section, is given by an exponential decay function,

$$m = m_o e^{-\alpha t} \tag{5}$$

where m_o is the initial rate of material release and α is a parameter quantifying how rapidly the release rate goes to zero. Substituting Eq. (5) into Eq. (4) yields after some calculation,

$$c(x,t) = \frac{m_o}{A\sqrt{\pi D}} \exp\left(-\alpha t + \frac{xU}{2D}\right) \int_0^{\sqrt{t}} \exp\left(-\left(\frac{C_1}{t'^2} + C_2 t'^2\right)\right) dt' \tag{6}$$

where the coefficients C_1 and C_2 are defined as:

$$C_1 = \frac{x^2}{4D}$$
$$C_2 = \frac{U^2}{4D} + \frac{w}{h} - \alpha \qquad (7)$$

The integral in Eq. (6) may be developed in terms of elementary functions, where the solution depends on the coefficient C_2. If $C_2 > 0$, then the solution contains a sum of real-valued error functions; however, for $C_2 < 0$, the solution will include complex-valued error functions (Abramowitz and Stegun, 1965). Due to limited space, the solutions involving the development of the integral will not be given here.

4.3 Characteristic quantities for concentration

Analytic solutions make it possible to identify the governing parameters of the problem at hand, as well as to develop non-dimensional quantities that can characterize the main features of the solutions. Such quantities can also be useful in fast and simple predictions as a basis for decision-making in connection with a pollution release. In the following, some non-dimensional quantities will be developed based on Eq. (2) that can be potentially useful for the initial assessment of the impact from a landslide event.

At a specific location away from the point where the mass of sediment is released (e.g. slide area), the concentration variation in time is in general not symmetrical (compare frozen cloud assumption) and the specific time when the maximum concentration is recorded at a location x_o depends on the value of the three parameters U, D, and w. Solving for when $\partial c/\partial t = 0$ at x_o (Eq. 2) yields the following equation for the time $t_{\max}$ when the maximum concentration is observed,

$$\frac{t_{\max}U^2}{D} = \frac{1}{1+4\frac{wD}{U^2h}}\left(\sqrt{1+\frac{x_o^2U^2}{D^2}\left(1+4\frac{wD}{U^2h}\right)}-1\right) \qquad (8)$$

where the following non-dimensional quantities may be introduced,

$$\xi = \frac{t_{\max} U^2}{D}; \quad \lambda = \frac{wD}{U^2 h}; \quad \chi = \frac{x_o^2 U^2}{D^2} \tag{9}$$

making it possible to express Eq. (8) as:

$$\xi = \frac{1}{1+4\lambda}\left(\sqrt{1+\chi(1+4\lambda)}-1\right) \tag{10}$$

Figure 3 plots ξ as a function of χ for various values on λ based on Eq. (10). Using Eq. (2) with $t = t_{\max}$, where $t_{\max}$ is obtained from Eq. (8), gives the maximum concentration at $x = x_o$. The non-dimensional expression for the maximum concentration is,

$$\sigma(\lambda,\chi) = \frac{1}{\sqrt{4\pi\xi}}\exp\left(-\frac{\left(\sqrt{\chi}-\xi\right)^2}{4\xi}-\lambda\xi\right) \tag{11}$$

where ξ is given by Eq. (10) and:

$$\sigma = \frac{c_{\max} AD}{MU} \tag{12}$$

The type of quantitative information provided by Eqs. (10) and (11) may be useful for predicting the impact of a sediment release in connection with a landslide. Figure 4 shows σ as a function of χ for various values on λ based on Eq. (11).

It may be interesting to look at the asymptotic properties of Eq. (8) for various limits to the governing parameters U and D. If $D \rightarrow 0$, then $t_{\max}$ will approach x_o/U, that is, the maximum will occur at a time given by the advection speed only (satisfies the frozen cloud approximation). On the other hand, if $U \rightarrow 0$, then:

$$t_{\max} = \frac{h}{4w}\left(\sqrt{1+4\frac{x_o^2 w}{hD}}-1\right) \tag{13}$$

which for the case of $w \rightarrow 0$ implies $t_{\max} = x_o^2/2D$.

5 Comparison with data

5.1 Agnesberg landslide

The Agnesberg landslide occurred on the 14 April 1993. It took place within an industrial site located on the eastern bank of the southern branch of the Göta River, some 10 km upstream central Gothenburg and about 2.6 km upstream the fresh-water intake at Lärjeholm (Fig. 2). The affected land area ultimately reached about 2400 m^2, with an approximately 80 m long and 30 m wide stretch of the riverbank having slid into the river through a retrogressive, rotational movement involving in total approximately 8000 m^2 (Larsson et al., 1994). The river was partially dammed since a portion of the cross section was covered in a 2-m thick layer of sensitive clay (Larsson et al., 1994). The site of failure was located within and along a stretch of the river characterised by thick (about 33 m deep) deposits of compressible and sensitive clay resting upon extensive deposits of sand with interbedded silt and clay layers (Larsson et al., 1994). The uppermost 13 m of the clay layer was classified as highly plastic, containing plant and shell remnants with contributions of mud. Beneath, the clay transcends into a sulphide spotted moderate plastic clay with some shells. Quick-clay was known to be present and geotechnical studies later detected substantial artesian groundwater pressures within the sand layers. Towards the north, the slide area was limited by a distinct change in the soil stratum in the form of 4-m thick fluvial sediment of sand and silt deposited in and around a passing creek. Topographically, the land area can best be described as somewhat superficially flat with the uppermost soil layer composed of filling material, resting above clay containing plant and shale remnants with some contribution of mud. The bottom profile at the site for the event was reconstructed based on adjacent sounding and geotechnical investigations. The bank shelf probably formed a 24-m wide shallow section with a water depth slowly increasing from 1 m closest to the bank to about 2 m at the deep end. The bank ended with a steep subaqueous slope with an estimated height of 6 m and a slope angle of about 1 : 1.5 (Larsson et al., 1994).

The landslide involved three distinct slides (events). The first slide represented the initiating slope failure of the subaqueous slope, mainly composed of fine sediments with a dominance of clay. The second (main slide) and third slide (retrogressive slide), on the other hand, involved land areas where the top layer is composed of filling material upon dry crust clay (possible with contribution of fluvial sediments). The landslide was classified as a rotational slide around a circular failure plane. Figure 5 illustrates estimated pre- and post-slide bottom profiles, probable failure planes, and the course of events.

Since no real-time observations were made at the slide location, the course of the slide events was subsequently developed based largely on recordings of turbidity made continuously at the Lärjeholm freshwater intake (mean values provided every minute). These also served to demonstrate the carrying capacity of a landslide of this magnitude. At the day of the landslide, three major sediment pulses were registered, hence indicating three successive slide events (Fig. 6). The first pulse was timed at approximately 06:00 a.m., whereby the level of turbidity increased from 4 to 9 FTU (Formazin Turbidity Units). The second pulse occurred roughly three hours later, demonstrating an even greater increase in turbidity going from 4 to 12 FTU. The third and last pulse was dated to about 12:30 p.m., 6 h after the initial event, during which the level of turbidity increased from 7 to 9 FTU (Larsson et al., 1994). Of the three events, only the two latter were actually witnessed by people. Based on ensuing studies, it was concluded that the movement ought to have started as a subaqueous slide along the underwater slope, in turn triggering and successively causing the main (second) and the third (last) slide event some three and six hours later, respectively (Larsson et al., 1994). Passing ships may also have influenced the course of events, potentially imposing transient stresses along the already sensitive reach. Dredging was later undertaken in order to restore the channel morphology. However, due to major concerns of further movements, stabilisation measures were first completed both on land and along the channel bed (Larsson et al., 1994).

Immediately after the slide, surface water samples were taken and analysed for selected physical parameters, such as nutrients, pathogens, mercury, and some chlorinated hydrocarbons. The result only showed a slight increase in chlorinated hydrocarbons, but this was assumed not to be a consequence of the slide (Göteborg Vatten, 2005). However, the samples were not taken in conjunction with the turbidity peaks but later, implying that any notable increase should be associated with erosion from run-out deposits and not with the pulse of SPM. Six sediment samples were taken from the run-out deposits 20 days after the event. The samples were analysed for some metals, PCB (polychlorinated biphenyls), EOX (extractable halo-organic compounds), and PAH (polyaromatic hydrocarbons). The result showed low levels of contamination with average concentrations: $<0.05\,\text{mg Hg kg}^{-1}$ dry mass; $0.18\,\text{mg Cd kg}^{-1}$ dry mass; $13.6\,\text{mg Pb kg}^{-1}$ dry mass; $11.8\,\text{mg Cu kg}^{-1}$ dry mass; $16.7\,\text{mg Cr kg}^{-1}$ dry mass; $10.6\,\text{mg Ni kg}^{-1}$ dry mass; $64.5\,\text{mg Zn kg}^{-1}$ dry mass; $<0.05\,\text{mg PAH kg}^{-1}$ dry mass; $0.81\,\text{mg EOX kg}^{-1}$ dry mass (Göteborg Vatten, 2005). The samples had an average content of 82.2 % dry mass and with a loss of ignition of 4.4 % of dry mass (Göteborg Vatten, 2005).

5.2 Parameter estimation

The focus in the comparison with the data was on the analytical solution given by Eq. (2). In order to investigate how well this solution can describe the measurements from the Agnesberg landslide, a number of quantities (or, parameters) in the solution must be specified. Some of these quantities are known or easily measurable, whereas other quantities may have to be estimated from the data through calibration. The number of quantities used for calibration should be kept to a minimum to provide the greatest confidence in the solution. In general, the following input quantities are required in the analytical solution describing the impact of a landslide:

- Hydrodynamic (U, A, h, and D)
- Sediment (w)

– Landslide (M)

The hydrodynamic quantities (U, A, and h) could be obtained directly from available measurements using averages over the river stretch of interest, whereas the dispersion coefficient is typically a difficult parameter to assess for a river (often determined from tracer studies). However, there is a multitude of empirical formulas available for D that will provide approximate values. The sediment properties were determined from river samples, whereas the total mass of sediment released through the landslide was more difficult to estimate (the total volume of the landslide was known, but not the portion of this volume that would contribute to the transport of SPM). Thus, in the end M was determined through calibration. Another unknown quantity that in principal requires calibration is the time of the landslide with regard to the time of measurements at Lärjeholm. Thus, the starting time of the landslide is set to $t = 0$ in the analytical solution, but this starting time should be related to the time of measurements to obtain the same reference for the solution and the data. In essence, a starting time t_o should be introduced for the measurements that corresponds to $t = 0$ in the model, and this value should be subtracted from the measurement times.

In a first approach, both M and t_o were used in the calibration process simultaneously. The sum of the least-square deviation (S^2) between measured and modelled concentrations was minimized to find optimal parameter values. The minimization was done through a "brute-force" approach where S^2 was calculated for a large number of combinations of M and t_o. However, it proved difficult to find a stable global minimum for S^2, because of the sensitivity to the value of t_o. The measured concentration variation with time involved a rapid increase towards the peak value, followed by a slower decrease back to the normal concentration (base level) in the river. Thus, small shifts in time of the concentration distribution may cause large changes in the value of S^2, although the agreement visually looks satisfactory. Another strategy was then devised to determine optimum parameter values. The emphasis in the calibration was put on M, whereas t_o was not included implying that the precise occurrence of the event in time was not described. In order to find the proper value on M, $t_{\max}$ from Eq. (8) was first calculated and then used together with the observed maximum concentration ($c_{\max}$) during the landslide event to determine M from Eq. (2). The shape of the calculated concentration distribution was then visually compared with the measured distribution without any consideration of the time of occurrence for $c_{\max}$.

The following values were employed for the river stretch between Agnesberg and Lärjeholm based on detailed measurements of the river morphology and flow at the time: $A = 640\,\mathrm{m}^2$, $U = 0.3\,\mathrm{m\,s}^{-1}$, $h = 4.1\,\mathrm{m}$, and $x_o = 2600\,\mathrm{m}$. Analysis indicated that a representative settling velocity for the sediment in the river is $0.002\,\mathrm{m\,s}^{-1}$, although the slide material might have had slightly different properties. The dispersion coefficient was calculated based on the river properties for the actual flow to be $230\,\mathrm{m}^2\,\mathrm{s}^{-1}$ using the formula proposed by Kashefipour and Falconer (2002), where a Manning's roughness of 0.04 was selected (employing the expression suggested by Deng et al. (2001) gave a value of $180\,\mathrm{m}^2\,\mathrm{s}^{-1}$; somewhat lower but still in the same range).

5.3 Predictions by the analytical solutions

Figure 7 illustrates the calculated and measured time variation in SPM for the first event in the Agnesberg landslide, where the SPM base level has been subtracted (estimated to $3.4\,\mathrm{mg\,l}^{-1}$, based on a general correlation between turbidity and suspended matter for the Göta River). The initial landslide mass (M) was determined to be 170 000 kg from Eq. (2). As discussed in the previous section, no attention was paid to the occurrence in time of the event (t_o) (note the arbitrary shift between the peaks in Fig. 7) and the landslide mass was calculated to produce the correct maximum observed concentration ($c_{\max}$). The general features in the observed time variation of $c(t)$ at x_o is reproduced by Eq. (2), although the measured peak tends to be narrower and the asymmetry in time around $c(t)$ a bit more pronounced.

This behaviour is even more pronounced when the second part of the landslide, containing two individual events, is simulated, as shown in Fig. 8. Also, after the second peak of the landslide (i.e. first peak in Fig. 8) a rather high concentration is observed before the third peak occurs that is not reproduced by Eq. (2). The analytical solution yields a more rapid decay towards zero concentration (above the base level), before the next event occurs. The predicted total mass of suspended sediment involved in slides two and three were estimated to $M = 215\,000$ and 130 000 kg, respectively. Measurements indicated that the landslide encompassed a total surface area of approximately 8000 m^2, which implies that about 0.6 % of the landslide released material was transported downstream as SPM, if a bulk density of 1600 $\mathrm{kg\,m}^{-3}$ (Larsson et al., 1994) is assumed and the slide depth is set to an average of about 7 m (the disturbed part of the rotational slide).

Sensitivity tests were performed by varying the values of the main parameters in Eq. (2) and observing the response of the shape for $c(t)$ (the fitting procedure still ensured that $c_{\max}$ was obtained, which affected the value of M). A larger value on D will produce a more asymmetric distribution with a narrower peak, more similar to the measured $c(t)$. In contrast, a smaller D yielded a more symmetric distribution, further away from the shape observed in the measurements. Regarding the initial mass of material released, larger D-values produced smaller M-values. Figure 9 illustrates how $c(t)$ responds to changes in D, where values 10 and 1/10 times the value predicted by the theoretical formulas (i.e. $D = 230\,\mathrm{m}^2\,\mathrm{s}^{-1}$) were employed. The increase in asymmetry for $c(t)$ as D increases is clearly seen in the figure, as well as how the arrival time for the peak at x_o decreases with increasing D. The more important advection becomes in relation to dispersion, the closer the time when $c_{\max}$ occurs will be to x_o/U, which is about 145 min (a value of $D = 23\,\mathrm{m}^2\,\mathrm{s}^{-1}$ approaches this limiting value). The value on the settling velocity (w) had a pronounced effect on M, but less so on the shape of $c(t)$, where a smaller w-value implied a smaller M-value. For fine material, the settling velocity will be low and the influence on the concentration distribution negligible. Thomas et al. (2001) performed field measurements in two streams and found poor correlation between the calculated settling velocity and the deposition rate estimated from the collected data. Their assessment was that for sediment sizes below the range 0.05 to 0.1 mm gravitational effects might be small.

In order to improve the agreement between the analytical solution to the ADE and the measurements, more complex solutions were investigated including superimposing two solutions for different sediment particle sizes (i.e. settling velocities) and describing the release of material through the landslide by using a time-varying function rather than an instantaneous source (see Eq. 6). The latter approach could potentially describe the asymmetry in $c(t)$ better than Eq. (2), if a suitable function for the release of landslide material is employed (e.g. Eq. 5). The former approach, using for example two different sediment sizes, where one is coarser and one finer, could produce a slower overall decay in $c(t)$ with higher concentrations at the tail, as was observed, particularly after the second event (see Fig. 8).

The calibration process to determine the optimum value for M in these more involved solutions, as well as the values of new parameters introduced (e.g. α), becomes increasingly complicated and trial-and-error techniques must often be used. Figure 10 illustrates how well Eq. (6) can describe the first landslide in the Agnesberg event, where $M = 190\,000$ kg and $\alpha = 0.001\ \mathrm{s}^{-1}$ were employed. The value on α (Eq. 5) was arbitrarily set and implies that the rate of mass transport has decreased to 15 % of its initial value after 30 min. The larger the value on α is, the closer Eq. (6) becomes to Eq. (2). The figure shows that introducing a finite release of material from the landslide using Eq. (5) yields limited improvement for the studied case: the tail of the calculated distribution slightly improves, but the rising phase is less well described (has a lower gradient) and the distribution around the peak is too wide.

Employing two different sediment sizes and superimposing the solutions obtained from Eq. (2), a more asymmetric shape on $c(t)$ may be simulated. However, more quantities emerge that needs to be assigned values, unless information from the landslide is available. No particle grain size analyses were done in connection the geotechnical analysis, but a good estimate for the clayey layer is a general particle size of 0.002 mm. It is more difficult to estimate a general particle size for the second (main) and the third (retrogressive) events that also contained filling material and possibly fluvial sediment, but it is reasonable to assume a particle size in the silt and sand fraction. Thus, the two solutions both need an initial sediment mass released, implying more complex calibration with less generality in the results. Figure 11 illustrates the result from using two analytical solutions to represent the release and transport of two sediments with the settling velocities 0.002 m s^{-1} (associated with concentration $c_1(t)$) and 0.0002 m s^{-1} (concentration $c_2(t)$). The second sediment was given a much lower settling velocity in order to reproduce the extended tail observed in the measurements. This difference in settling velocities are reflected in the M-values obtained, which were 140 000 kg and 7000 kg, respectively. The overall shape of the distribution is well described, but the width is too large. Further manipulation of the settling velocities and the initial sediment mass released would yield better agreement, but would produce optimum values that are difficult to justify with regard to the conditions during the Agnesberg landslide. It may be easier to improve the agreement with measurements for event two and three using a solution involving two grain sizes, since the tail drops off at a markedly slower rate than for these two slides compared to slide one.

5.4 Mass transport and contaminant release

For the three individual slides, using the analytical calculations above, it can be estimated that that about 0.6 % (515 000 kg) of the total soil mass went into suspension/was suspended and was transported downstream, which is reasonable considering the type of landslide that occurred. This instantaneous release corresponds to about 1 to 2 % of the annual suspended sediment delivery for that river stretch (Göransson et al., 2011). The suspended sediment concentration in the river water increased about 2.5 times the base level at the time for the slide. The suspended sediment transport increased from about 0.5 kg s^{-1} to 1.3 kg s^{-1} during the first and submerged slide, to 1.4 kg s^{-1} during the main slide and 0.7 kg s^{-1} during the third and retrogressive slide. Under the assumption that the concentration in the run out sediments from the sediment sampling also are valid for the suspended sediments that were released, the landslide event caused an instantaneous release of about 0.1 kg cadmium, 7 kg lead, 6 kg cupper, 8.5 kg chromium, 0.5 kg nickel, 33 kg zinc, and 0.5 kg

EOX (PCB was under the detection limit). This corresponds to between 0.1 and 0.5 % of the total annual load for the measured substances based on data from the year 2010 (see GÄVVF, 2011).

6 Discussion

6.1 Analytical approach to describe sediment release from landslides into a river

Different analytical solutions to the ADE were tested against the measured data from the shallow rotational, retrogressive landslide in clayey sediments that took place 1993 in the Göta River, SW Sweden. The landslide encompassed three distinct events, namely an initial submerged slide, followed by a main slide, and a retrogressive slide. These slides generated three distinct peaks in the online turbidity recordings at the freshwater intake downstream the slide area. To our knowledge, this registration of the impact in a river of the sediment release from a landslide is one of the few of its kind in the world, and unique for Sweden considering the low frequency of landslide events, making it highly useful for evaluating how appropriate the ADE is to describe a landslide into surface water.

The classical analytical solution to the ADE for an instantaneous release of a fixed amount of material (M) to a river produced satisfactory agreement with the observations. In the comparison with the data, almost all quantities were measured or estimated from available formulas except M, which was back-calculated from the measured maximum concentration. The asymmetric shape of the observed concentration distribution in time was reproduced by the solution, but the width of the distribution was overestimated. Also, for the second event (main slide), the decay rate for the measured concentration was lower than for the calculated. By modifying some of the main parameters, particularly the dispersion coefficient (D), improved agreement is obtained, especially with regard to width of the distribution. A larger D will produce a narrower, more asymmetric distribution in line with the measurements. However, values on D that yield the best agreement tends to be in a range that is non-physical.

More advanced solutions were employed to improve the agreement, including having a sediment release that is a function of time and employing different sediment grain sizes. In the former case, a slightly better fit was obtained for the tail of the distribution, but the width was still overestimated. Using two grain sizes with different settling velocities could also give better agreement for the tail-end of the distribution; again, the distribution was too wide. Furthermore, the difference in M between the two grain sizes in the solution was significant and not very realistic.

6.2 Implications for water quality management

For the present landslide, it was found that only a small part of the displaced soil instantaneously came into suspension (about 0.6 %) and that most of the material remained at the site in the river. The cohesive forces in the clayey sediment and the shallowness of the landslide can probably explain this. Landslides in cohesive soils, such as rotational slides, translational slides, and slumps, often form the movement of coherent soil clods around a slip surface, in contrast to other mass movement such as debris falls, debris/mud/earth flows, and debris avalanches in friction soil, where particles loose contact, starts to mix and behaves more like a liquid. Also Schwab et al. (2008) confirmed that only a fraction of material displaced by earth slides may be released to the sediment routing system, nevertheless, Schwab et al. (2008) argued that “landslide has to be considered as a point sediment source in the drainage basin, and therefore its influence on the sediment budget of the whole basin might be marginal”. The instantaneous release of material, even though at a small rate, can reach several tons, if the landslide is large enough, causing high concentrations in the water for a limited period of time. In river or lake waters that normally have low turbidity, such a sudden increase may cause harm to sensitive species.

For the studied case, the landslide partly involved an industrial area with possible soil contamination from diffusive leakage or accidental spills. Sediment samples for the displaced soil and water samples taken some time after the landslide event indicated low contamination. However, no sampling was done in conjunction with the event. In this study, we used the results from the ADE solution, together with results from the sediment sampling, to estimate the probable instantaneous release of some metals and organics that could be associated with the release of suspended sediment. Even though there are uncertainties, the result indicated that several kilos cupper, lead, and chromium were released with each of the three slides, yielding a total load of 6 to 8.5 kg for each metal, together with about 30 kg zinc, 0.5 kg nickel, and 0.5 kg extractable organic halogens. As we do not know the total content of the contaminants in the displaced soil mass, we cannot assess the rate that was released, neither can we assess the ratio between dissolved and particle bound contaminants as it depends on the biogeochemical conditions.

The additional suspended sediment load and pollution load from the Agnesberg landslide may seem small, but then one have to keep in mind that this was a minor slide with a surface area less than 2 % of the largest landslides in the area. Also, the soil contamination at the site was considered low according to the national method for risk assessment of contaminated soil with a scale including low, moderate, high and very high risk (Naturvårdsverket, 1999). Nevertheless, it indicates that even small mass movements may affect the overall water quality, both in terms of chemical and physical properties, and that large slides do have the potential to yield large impact on water quality. This also demonstrates that landslides are possible sources of pollution and ought to be considered in the risk analysis for landslide hazard, as well as for contaminated land and water quality management.

As pointed out previously, the possible shifts of pollutants from particulate states towards dissolved species have large implications for the health and ecological risks as dissolved species have a higher bioavailability. In the sediment the large fraction of heavy metals is bound to particles. The desorption of pollutants from sediments becomes an important source for dissolved species as they are brought up in the water column with altered geochemical conditions (Goossens and Zwolsman, 1996). This effect should be acknowledged in risk assessment.

Sedimentation, diffusive, advective, and break-down processes have impact on both concentrations and quantities that ends up at a particular location (e.g. lake or estuary). Even though the slide itself does not involve areas with possible contamination, the run-out or generated impulse wave may cause damage to nearby-located industries or landfills (organic and inorganic pollutants), and fertilized agriculture (nutrients) or pastureland (e-coli from faecal). In Bonnard et al. (2004), for example, the risk for the destruction of a chemical industry downstream a European mountainous area sensitive to landslide was pointed out. Thus, there is a lack of knowledge about the consequences for the ecosystem that landslide-induced mobilisation of contaminants may cause. It is, however, probable that such studies will be required in the future, especially in areas where precipitation is expected to increase, since a large part of all landslides are induced by rainfall.

7 Conclusions

Data on turbidity collected in connection with a minor landslide into Göta river, SW Sweden, showed that the suspended sediment concentration downstream the release point exhibit a non-Gaussian variation with time, being strongly skewed. Even so, applying classical analytical solutions to the ADE for describing the effect of a landslide into surface waters can yield realistic predictions of the resulting concentration distribution in the river, if the initial conditions at the landslide site are known. Most parameter values in the ADE are straightforward to obtain through measurements at the site of interest, but some parameters may require detailed investigations, for example, the dispersion coefficient and amount of sediment that is likely to go in suspension during a landslide. In general, the maximum concentration and the time when it occurs are the most important quantities to predict for analysis, risk assessment, and operational purposes. These two quantities are easily obtained from analytical solutions to the ADE. Overall it can be concluded from this study that even if the 1-D ADE represents a marked simplification of the complex processes that govern the transport and mixing of suspended material in the river in connection with a landslide, the equation provide a good description of the recorded data and it can be employed as a useful analysis tool coupled to existing risk assessment models. Based on the analysis of the data from the landslide in the Göta River, involving a part of an industrial site, it can also be concluded that mass movements are possible sources for the release of contaminants and the ADE provides a good first approximation for the assessment of possible environmental risks, if the initial conditions can be specified. However, further and more detailed studies are needed to find more accurate description of the transport processes. There is also a need to increase the knowledge on possible environmental consequences in the near and far field, in a short and long-time perspective.

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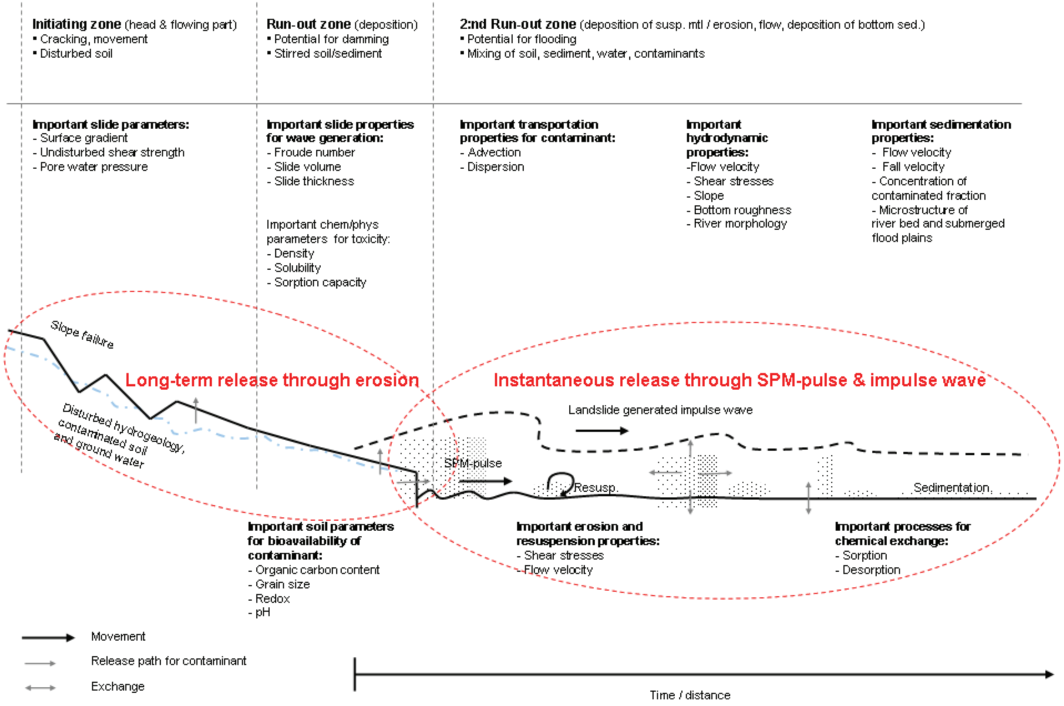

Fig. 1. Schematic description of the release of contaminants into surface water from a landslide (further developed from Göransson et al., 2009). In landslide nomenclature, the zone where a mass movement is initiated is referred to as the "initiating zone", and the zone where deposition takes place is in general referred to as the "run-out zone". The illustration describes how the event can be divided into three zones depending on processes, and the governing process parameters in each zone. After the event, the release and transport of contaminants can be divided in to an instantaneous release and a long-term release (dashed ovals).

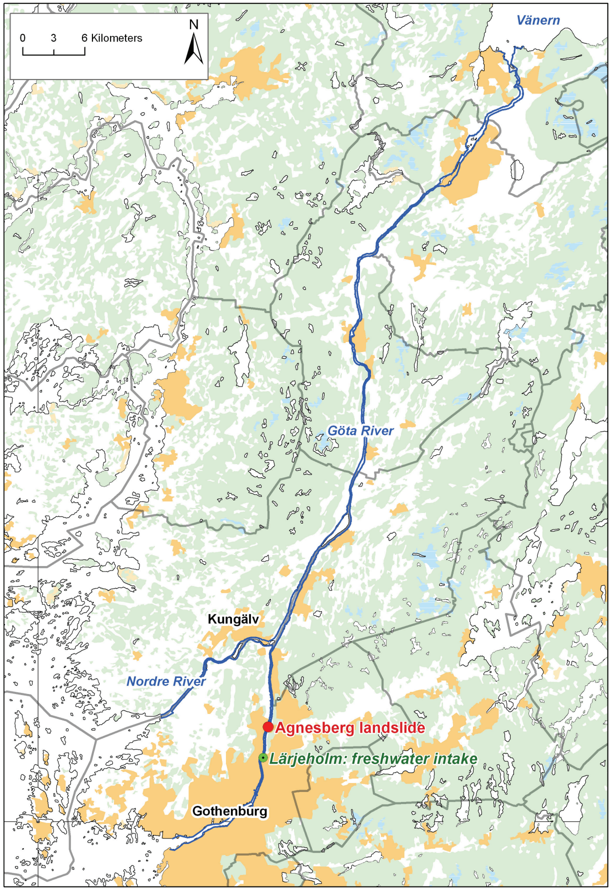

Fig. 2. The Göta River study area showing the locations of the Agnesberg landslide and the freshwater intake (Background map© Lantmäteriet).

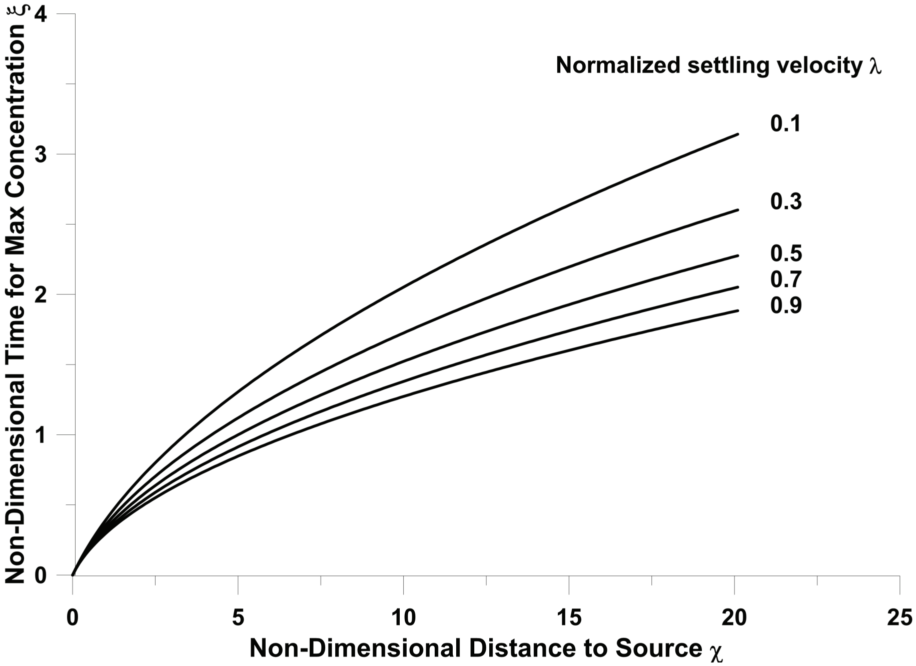

Fig. 3. Non-dimensional *time* for the occurrence of maximum concentration at a particular location away from a pollution release as a function of non-dimensional distance and fall speed.

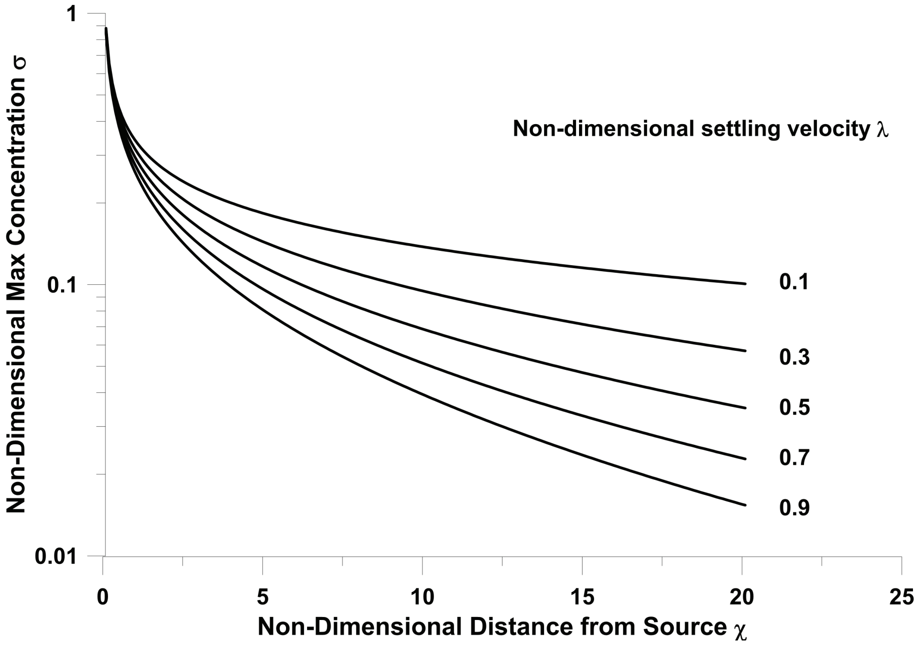

Fig. 4. Non-dimensional *maximum concentration* at a particular location away from a pollution release as a function of non-dimensional distance and fall speed.

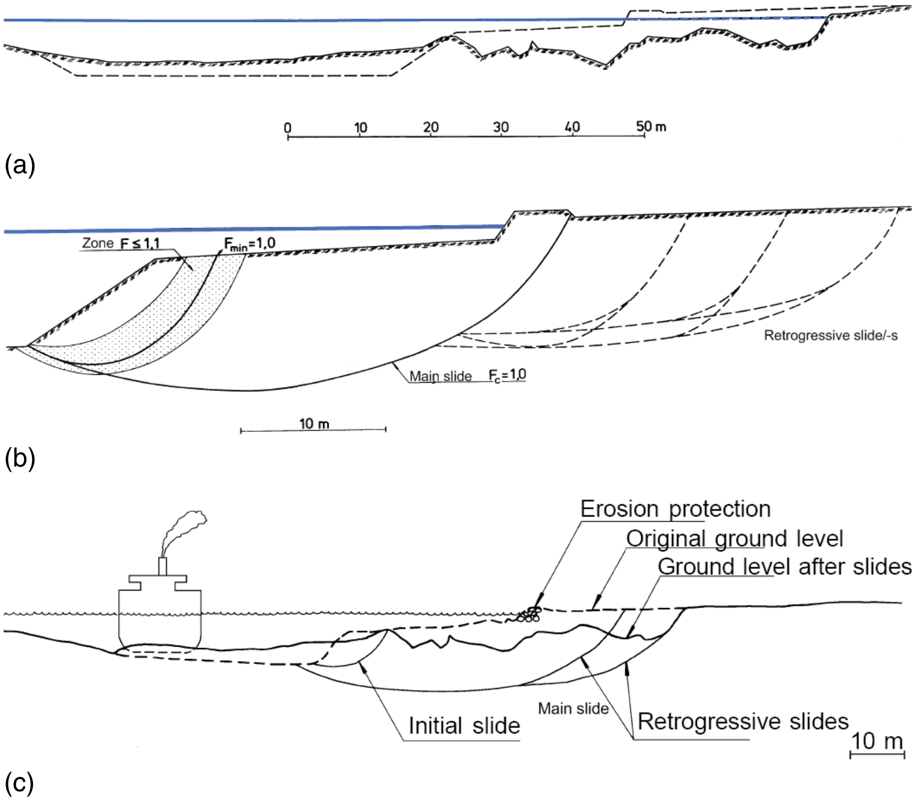

Fig. 5. **(a)** Estimated pre-slide (dashed line) and surveyed post-slide (cross-hatched line) transect of the affected reach of the river, and approximated water level (blue solid line), **(b)** calculated failure planes and, **(c)** probable course of event. (F = factor of safety, F_{min} = minimum stability factor, and F_c = F with respect to cohesion.) Adopted from Larsson et al. (1994).

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

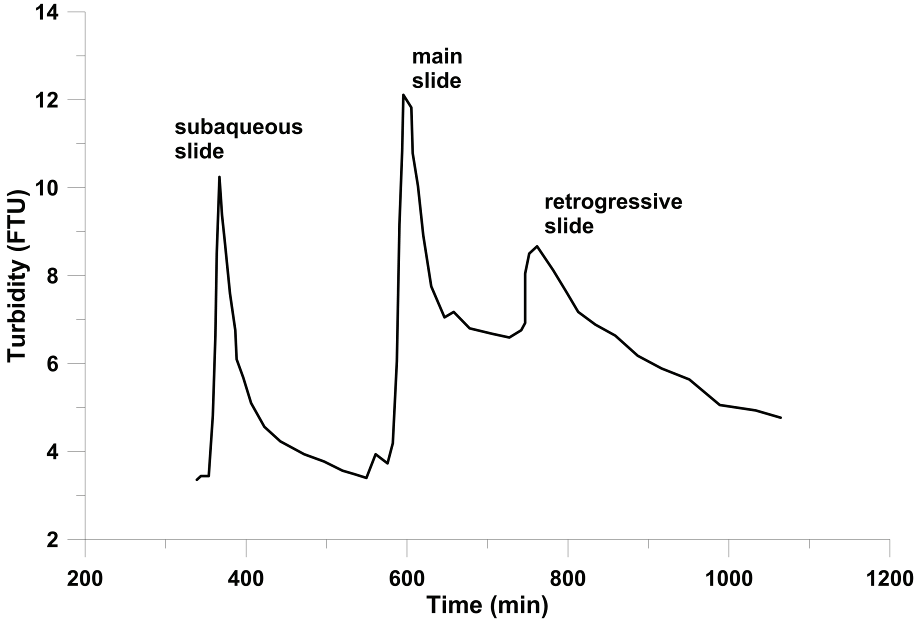

Fig. 6. Measurement of turbidity at Lärjeholm 2.6 km downstream the site and at the day of the slide. Adopted from Larsson et al. (1994).

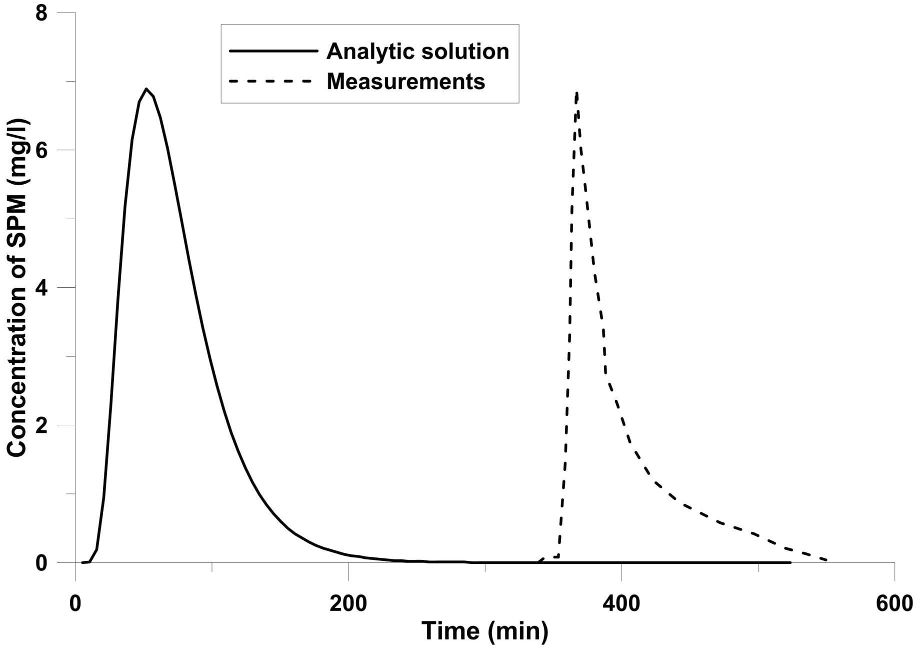

Fig. 7. Calculated and measured variation in SPM concentration with time for the first and initiating event in the Agnesberg landslide using a dispersion coefficient of $D = 230\,\mathrm{m}^2\,\mathrm{s}^{-1}$.

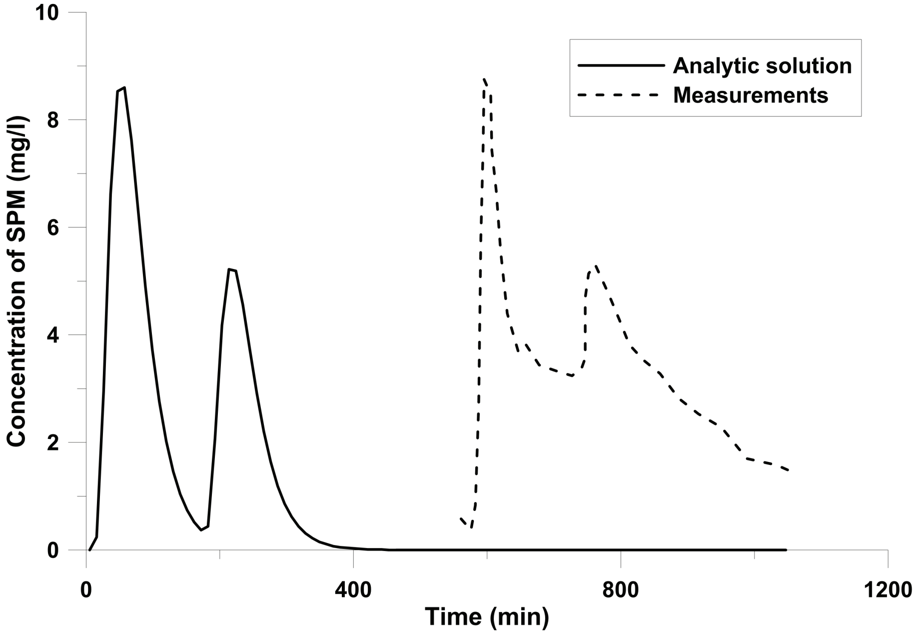

Fig. 8. Calculated and measured variation in SPM concentration with time for the second and third event in the Agnesberg landslide using a dispersion coefficient of $D = 230\,\mathrm{m}^2\,\mathrm{s}^{-1}$.

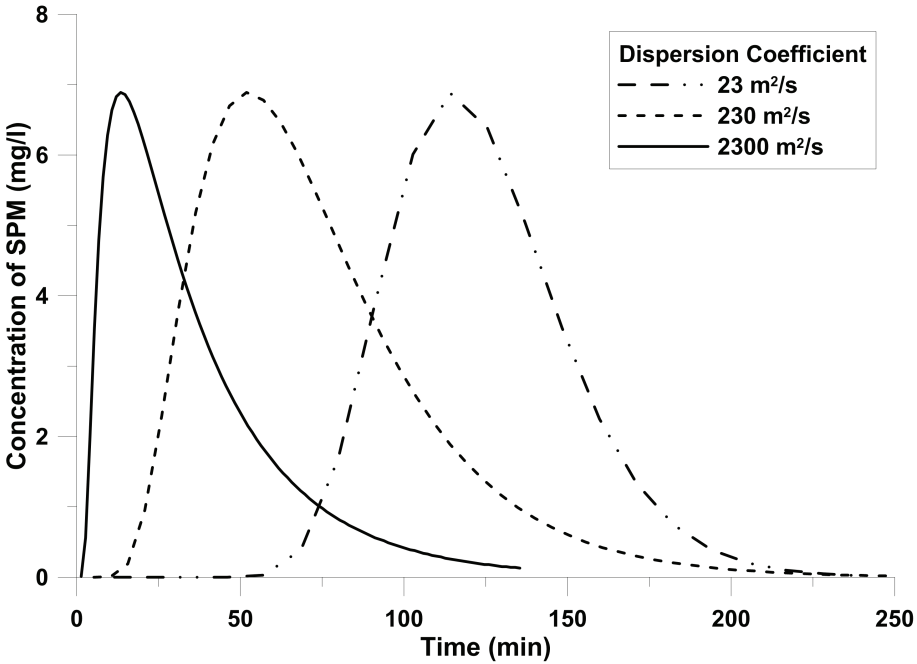

Fig. 9. Calculated variation in SPM concentration with time for the first event in the Agnesberg landslide using different dispersion coefficients.

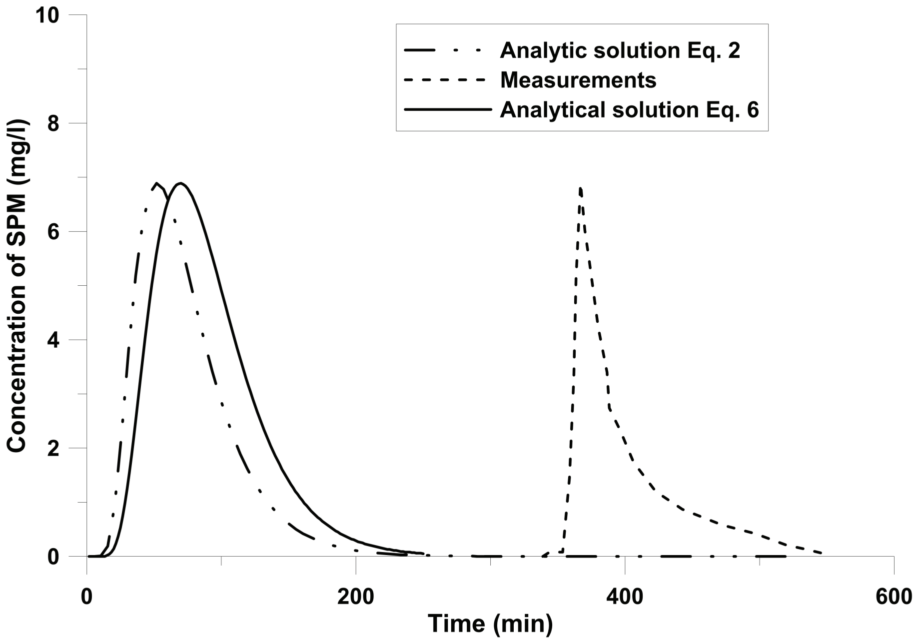

Fig. 10. Calculated and measured variation in SPM concentration with time for the first event in the Agnesberg landlside using two different analytical solutions (Eqs. 2 and 6).

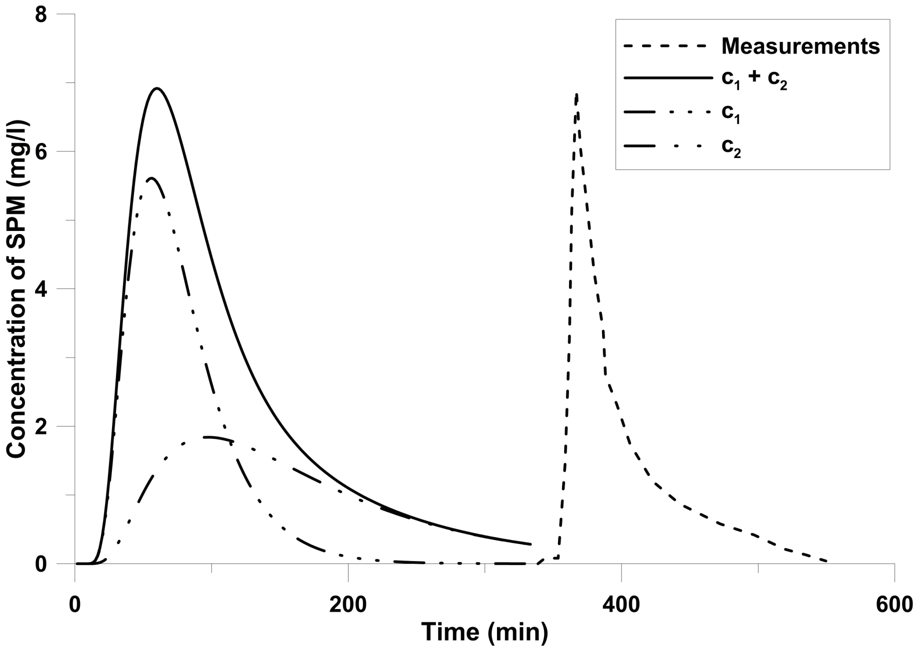

Fig. 11. Calculated and measured variation in SPM concentration with time for the first event in the Agnesberg landslide using the combined effect of two different sediment sizes.