

Journal: HESS

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

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MS No.: hess-2011-329

MS Type: Research Article

## Authors' response to the reviewers' comments

### General

The comments provided by two reviewers are very constructive and helpful, and will greatly improve the paper. Their efforts will be acknowledged.

In the following a detailed rebuttal is presented where changes that will be made in the paper are discussed in the context of the review comments provided. If some suggested changes are not planned to be carried out, this is motivated in detail by the authors.

### Referee no 1

#### General comments

Referee no 1 concludes that there will be significant value in publishing: (1) the analysis, based on simulation of convective/dispersive/settling processes, of a recorded event of the downstream transport of landslide material; (2) some information on the recorded event; and (3) some information on the potential for water quality impacts of the landslide entering the stream. In doing so the referee strongly suggests that we substantially re-write, concisely edit, our manuscript to sharply focus on these three aspects and specifically on the original work we have done.

**Answer:** The authors intend to follow this advice closely by cutting some less relevant material, concentrating on the unique contribution of the paper, and putting the results into the context of previous studies. At the same time, an important aspect of the study is the landslide event and the material input provided by such conditions, making it necessary to cover some basic features of this type of event.

#### Issue #1 (transport analysis)

**1A, remark:** The referee strongly suggests that we focus our presentation of the simulation analysis around discussion of how our work adds to the authors Karwan and Saiers, 2009; Thomas et al., 2001; Paul and Hall, 2002; Huang et al., 2008, having previously used simulation of convective/dispersive/settling processes to help us better understand surface water fine particle transport.

**1A, answer:** Our modeling connects well to these studies, employing similar theory to our particular case (landslide event), but it also extends the theory to a few more cases, for example, a sediment release following an exponential variation with time and modeling the transport for several different grain sizes. Additional references to these studies will be included as well as a more detailed review of the particular modeling approaches taken.

**1B, remark:** Is eq (5) - the exponential release function - a new idea in your work? Has this form been previous used in analysis of fine particle transport? Is there any evidence for laboratory/flume/stream studies supporting use of this form. If its use here is simply ad hoc, I think that is OK - but that needs to be explicitly stated.

**1B, answer:** This is a new solution developed in this study. The motivation for the exponential shape function is indeed ad hoc; however, it contains some of the expected behavior associated with the

release of material in connection with a landslide. Initially the release rate should be large, but over the time scale of the slide, this rate should decay towards zero.

**1C, remark:** Section 2.3 (Suspended sediment transport and distribution) There is very little in this section about 'Suspended sediment transport'. Essentially the entire section is about 'distribution'. Unfortunately almost all of the text about distribution is about skewed distributions – for which your analysis does not account. Much of the discussion is then about some of the Transient Storage Models – which your analysis does not included. I suggest removing essentially all of this section. If you do want to say something the various storage processes which do influence fine particulate transport, then consider the work of A.I. Packman; I suggest starting with the review chapter in book *Streams and Ground Waters* (2000) (edited by J. B. Jones and P. J. Mulholland, Academic, San Diego, Calif.) If you do want to say something about the influence of transient storage processes on solute transport pulses & real field data, then I suggest starting with the analysis of R. L. Runkel: *Toward a transport-based analysis of nutrient spiraling and uptake in streams* Runkel, R.L. 2007 *Limnology and Oceanography: Methods* 5 (JAN), pp. 50-62.

**1C, answer:** This section will be rewritten and given a focus in accordance with the reviewer's suggestion. We will discuss the traditional approach with a symmetric distribution in space (which may give rise to an asymmetric distribution in time, since the diffusion and sedimentation changes the distribution as it is advected downstream passed a certain point) and then include material about various storage/transport processes and how they influence the distribution.

**1D, remark:** Start time,  $t_0$  & Figures 7 & 8. I fully appreciate the difficulty you face in not knowing the 'start time' of the landslide's erosion in the stream channel. You have to pick 'sometime' to start, so why not - by-trial&error - pick a simulation event start time that brings you close (or at least closer) to matching the peak times in the measurements and the simulations? The obscuring aspect of the simulations as presented is that the influence of the processes of the material release, dispersion, and settling change with time – the more time, the more release, the more spreading, the more settling. As presented the pulse of particulates for the simulation have been in the stream roughly 4 times as long as the measurements indicate.

**1D, answer:** In principal we can estimate with (varying) confidence most parameters in the analytical solution except the initial amount of sediment released ( $M_0$ ; note this is primarily an amount released into the river, not material that is eroded from the stream) and the time when this occurred with reference to the measurements of the turbidity. Originally we tried to apply a more sophisticated approach where both these parameters were estimated through a least-squares technique, but it is difficult to obtain a clear global optimum. Instead a different approach was taken where the time for the occurrence of the maximum concentration at the measurement point ( $c_{max}$ ) was calculated based on the known parameters. This time was used in the analytical solution to back-calculate  $M_0$  from the knowledge of  $c_{max}$ . Since we have no way of finding out the time difference between the event and the start of the observation, we cannot derive information about this difference, besides through an approach similar to the one we took initially. The shift in the figures between the analytic solution and the measured distribution is purely arbitrary for display purposes. We can plot the two curves with the same  $t_{max}$ , but feel it is easier to appreciate the details of the curves if we separate them. It is true that the relationships between the main governing parameters are complex and we will try to clarify our discussion. In the calibration phase all parameters, except  $M_0$ , are specified, so there are no degrees of freedom. However, subsequently in later figures the effect of changing various parameter values are investigated and then things might be more difficult to follow. If, for example, the dispersion coefficient is increased,  $M_0$  has to increase to achieve  $c_{max}$  since the distribution spreads out faster. Again, we will try to clarify and add some discussion that makes it easier for the reader to understand the relationships between the main parameters.

**1E, remark:** Settling velocity (Figures 3 & 4). I found the placement of Figures 3 & 4 before the main results to be distracting. I wanted to see how your analysis worked out with real data. The single

sentences in the text referring to each of the figures truthfully tell your readers nothing - expect that the figures exist. I suggest removing these figures (& the two sentences). If you do want to include some information on the influence of settling velocity then I suggest adding at the end of your results some parameter variation simulations as you have presented in Figures 9, 10 & 11.

**1E, answer:** We feel that these figures are of value to the reader, showing the dependence of  $t_{max}$  and  $c_{max}$  on the main governing parameters (not only the settling velocity). Also, they can be used for quick and simple estimates of  $t_{max}$  and  $c_{max}$  resulting from a sudden material release for practical purposes. However, we agree that more comments concerning what they show are needed and we will add this. We will consider moving them to a place later in the paper or present them in a different way.

#### Issue #2 (the event)

**Remark:** I think the majority of the information in the current manuscript is simply distracting from the main value of your work. There is far too much detail in this manuscript on the event and mechanics of landslides that does not add to our understanding of the downstream transport and the transport analysis actually performed. Additionally I wonder how much of the information currently in this manuscript can already be found in: Combining landslide and contaminant risk: A preliminary assessment: A study of the Göta Älv river Valley, Sweden Göransson, G.I., Bendz, D., Larson, P.M. 2009 Journal of Soils and Sediments 9 (1), pp. 33-45.

**Answer:** The authors acknowledge the advice from the referee and will carefully go through the text, remove text that is not relevant, and refer to information given in: "A preliminary assessment: A study of the Göta Älv river Valley..". However the authors believe that the description of the landslide process is important as it dictates the conditions at the upper boundary of transport domain.

#### Issue #3 (potential contamination impacts)

**Remark:** see that you have one result, the calculated mass of various metals likely associated with the sediments released in the event. I think there is far too much introductory and speculative text (Section 2.2 & 6.2) relative to presented results. Again, I find this - not 'wrong' - but rather, quite distracting – the result you do have is almost lost amid all of the text.

**Answer:** Our suggestion is to move, and also mitigate, most if this to discussion instead.

### **Referee no 2**

#### General comments

Referee no 2 concludes that this paper highlights a source of contaminated sediment entering rivers that has not been well studied previously. Other studies have reported on contaminated mining material contributed to river systems, but the mechanism for sediment introduction in this case is a landslide. The situation presents an excellent opportunity to study the transfer of contaminated material downstream because frequent turbidity measurements downstream of the landslide were available during the failure events. The paper is well organized and clearly written. The title and abstract are clear, and the figures are helpful to the understanding of results. Previous studies are properly credited. The authors use the advection-dispersion equation (ADE) to model sediment transport, and this equation has been widely used in a variety of applications. Besides the standard ADE, the authors also tried more complex solutions using different sediment particle sizes and by using a time-varying function rather than an instantaneous source. The authors make the point that large landslides do have the potential to be a source of pollution and should be considered in landslide risk analyses, which should be of interest to the readers of HESS.

### Questions and answers

Referee questions (Q) and authors answer (A) to these are given below. All technical corrections noted by the referee will be taken care of.

**Q1:** P. 10592 L. 21. Re: Long-term release of contaminants takes place through erosion of the run-out of the slide. Does erosion of the landslide scar also contribute additional contaminants?

**A1:** Most likely yes as contaminants may lay bare and hence are exposed for diffusion, surface erosion (wind, water), ground water transportation and so on, however we do not know the contribution to surface water quality.

**Q2:** P. 10598. What is the drainage area of the Gota River? It would be helpful on Figure 2 to include an inset map of Sweden showing the location of the Gota River.

**A2:** Göta River catchment area and the drainage area for the lower, studied, part is now included in the text. A figure will be added showing the total catchment.

**Q3:** P. 10606: What was the discharge at the time of failure?

**A3:** In the calculation, flow velocity is the interesting variable and not the flow. However, the velocity is based on measured river flow x km upstream the branching at the time of the event. Estimated flow at the site was estimated to 180 m<sup>3</sup>/s based on the run time from the measured point in Lilla Edet to the fresh water intake.

**Q4:** On P. 10610 discharge is estimated to be between 180 and 230 m<sup>2</sup>/s. The units should be m<sup>3</sup>/s. What is the recurrence interval of this flow – is this considered to be a high flow event? Was the landslide triggered by a rainfall event?

**A4:** 180 and 230 m<sup>2</sup>/s refers to the dispersion coefficient, not river flow. The sentences will be rewritten to make this clear. Nevertheless, the mean flow for the river stretch is about 158 m<sup>3</sup>/s, with a minimum of 99 m<sup>3</sup>/s and a maximum of 255 m<sup>3</sup>/s (year 2001-2010). A river flow of 180 m<sup>3</sup>/s is hence a bit over the mean flow. The landslide started as a subaqueous slide induced by erosion (not triggered by rainfall). This information will be included in the paper.

**Q5:** P. 10611 L. 5 states the landslide area was 8000 m<sup>2</sup>. Previously, on P. 10606 L. 6 the landslide area is stated to have an area of 2400 m<sup>2</sup>. Which is correct?

**A5:** The slide covered a land surface of 2400 m<sup>2</sup>, when including the subaqueous slide the total area was estimated to reach 8 000 m<sup>2</sup>. Sentence will be rewritten to make this clear.

**Q6:** Much of the landslide material was clay (P. 10606), yet the authors estimate that only 0.6% of the landslide released material was transported downstream as suspended particulate matter (SPM) (P. 10611 L. 6). How do the authors explain this low percentage of SPM?

**A6:** The dominating soil is clay but it is rather stiff and consolidated clay. The slides that do take place in the study area are dominated by rotational movements of coherent soil masses, meaning that it really is a slide, not a flow. The uppermost part of the moving mass consists of filling material above the clay, and also some sand. Also, the clay layer consists of thin silt and sand layers. The SPM that is created is probably material from the uppermost part that is more loosely packed, but also of disturbed river bottom sediment. The text will be rewritten to make this clear to the reader.

**Q7:** On P. 10615 they state that most of the material remained at the site in the river. Was this based on surveys or observation?

**A7:** Based on both. However, dredging was made to clear fare way, and geotechnical measures was undertaken to secure the site from further slides, but, if one would have left the slided material undisturbed, then erosion eventually would have moved material until new equilibrium would have been reached.

**Q8:** P. 10606 mentions a geotechnical investigation of the site, but it was not clear if any pre-landslide data were available.

**A8:** Geotechnical investigations were available from adjacent areas. The data was compared with data from the geotechnical investigation that was conducted on the site right after the event.

**Q9:** On P. 10598 the authors state the suspended particles in the Gota River are purely inorganic. P. 10608 L. 15 shows sediment samples after the slide had a loss of ignition of 4.4%. Did this represent organic material in the landslide-derived sediment?

**A9:** The sentence at P 10598 is corrected for the misunderstanding. The SPM transport in the river refers to the inorganic fraction of the SPM. If one includes the organic fraction the SPM transport is a bit higher as the organic fraction of the suspended sediment in the river varies up to about 25%. The 4.4% represents the organic material in the landslide deposits, yes.

**Q10:** P. 10615 L. 23. I agree with the authors that the impact of landslides is more than a marginal influence on sediment budgets. High turbidity in rivers may not only affect sensitive species but also affects other beneficial uses such as drinking water and swimming. Fig. 11 models two different sediment sizes with two different settling velocities, but what size particles do these represent, and are they realistic for the material actually involved in the landslide movement?

**A10:** Will add the influence on beneficial uses. The sediment sizes represent coarse and fine silt and are relevant for the released slide material (see A6).