Sprinkling Tests to Understand Hydrological Behaviour of Mudslide

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Abstract
The unsaturated zone buffers precipitation and controls groundwater recharges. Quantification of groundwater recharges is important for the improvement of hydrogeomorphological hazard analysis. The importance of fast preferential flow is recognized in literature, but its quantification remains difficult.

This paper presents the results from three 1 m² sprinkling experiments carried out in highly heterogeneous black marls of the Super-Sauze mudslide, in Southern French Alps. The aim of the experiments was to study the hydrological system within three morphological units characterized by different displacement rates and possible hydrological conditions. Special attention was given to identify and characterise the preferential flow patterns with the attempt for its quantification. The infiltration process was monitored with hydrological observations and hydrochemical tracers (Br⁻, Cl⁻). Based on the analysis of all available field data, conceptual models of the hydrological responses were proposed.

Keywords
Preferential flow • Sprinkling experiment • Active landslide

Introduction
The importance of understanding the hydrological system within a landslide is commonly accepted, however, including hydrological processes and their variability in landslide modelling is quite difficult and therefore often limited (Bogaard 2001; Lindenmaier 2007). In spite significant research attention given to advanced study of hydrological processes within landslide (e.g. Iverson 2000; Uchida et al. 2001; de Montety et al. 2007; Wienhöfer et al. 2011), their understanding is still limited especially because of the strong heterogeneity of landslide lithology and the spatial and temporal variations of the hydrological properties.

This is particularly true when dealing with highly heterogeneous clay shale slopes such as black marls. Additionally, in slow moving clayey landslides, the continuous opening and closing of fissure apertures by reworked sliding material occur (Bogaard 2001). Fissure networks provide preferential flow paths for infiltration and drainage. This changes the permeability of the soil influencing infiltration rates, saturation processes and groundwater recharges. The quantification of the groundwater recharge processes, in particular taking into account preferential flow, is a natural next step in advanced understanding of hydrological systems in hillslopes and landslides (Savage et al. 2003; Coe et al. 2004; Weiler and McDonnell 2007). Although the complexity of the processes and their high spatial variability make it very difficult to measure preferential flow in the field and to build...
up process models (van Schaik 2010). Nevertheless, a combination of hydrodynamic and hydrochemical responses observed during infiltration tests can give valuable information about natural preferential water pathways (e.g. Debieche et al. 2011).

This paper focuses on 1 m²-scale sprinkling tests using hydrochemical tracers (Br⁻, Cl⁻). The main objective of our research is to identify and measure the dominant hydrological process and its distribution across the mudslide. The sprinkling tests were carried out in three main morphological units of the mudslide in order to observe spatial heterogeneity in hydrological responses, with special attention given to preferential flow processes. The observations are then generalised into a hydrological concept of the behaviour of different hydromorphological areas within the mudslide and linked to the observed spatial distribution of the mudslide movements.

Site Description

The Super-Sauze mudslide (Fig. 1a) is a persistently active mudslide and consists of a heterogeneous clay-rich material containing reworked blocks and panels of marine at various stage of weathering (Malet et al. 2005). Infiltration of rainfall and snowmelt is the main source of groundwater, with limited water contribution from deep water sources along the major faults (de Montety et al. 2007).

Malet et al. (2005) divide the morphology of the Super-Sauze mudslide into three hydro-geomorphological units (Fig. 1a):
- Upper unit (HG1) – very active and very wet viscous muddy formation, with variety of crack systems,
- Western part of upper unit (HG2) – the most stable part of the landslide, with dense, compacted texture,
- Lower unit (HG3), which is stiff compact, impervious and stable formation with limited extension of cracked surface system.

The experiment plots were selected to represent morphologically different parts of the landslide: crumbly area near the crown (HG1), compacted stable part of the deposit (HG2) and active area which is muddy formation with width open fissures (HG1).

Methodology

Field Experimental Setup

Three 1 m² infiltration experiments were carried out, between 20 and 25 July 2008. For each plot, 2 days of 7–8 h artificial rain was applied with the use of a rain simulator. The rain was applied in time blocks of 15 min rain and 15 min break with average intensity of approximately 50 mm.h⁻¹. The tracing was realised with two tracers: Br⁻ during the first day of experiment and Cl⁻ during the second day of experiment. In order to protect the experiment from wind disturbances and to minimize evaporation the rainfall infiltration area was covered with a tent (Fig. 2).

Within each plot, 4–5 shallow piezometers were installed: one in the middle of the plot, 2 in the direction of expected (sub-) surface water movement (in the direction of fissures, if they were visible at the surface) and one uphill from the plot as a reference (Fig. 1b).

The depth of the piezometers is different at each area and depends on local hydromorphological conditions:
- Within plot A, all piezometers were installed at around 2 m depth;
- Within plot B, depths of the piezometers were determined by the presence of rocks in the soil and vary from 1.30 to 3 m;
- Within plot C, depths of the piezometers are around 1 m due to the shallow groundwater level.

Groundwater responses were monitored manually every 15 min, and with automatic water pressure devices every 3 min. The water for hydrochemical analyses was sampled every 1 h from all piezometers during the sprinkling experiment and one time per day for two consecutive days after the experiment.

Analysis Methodology

The analyses of the sprinkling experiments were done based on the water balance calculations (1) and mass balance for the tracer (2):
$P + GW_{in} = GW_{out} + OF + E + SSF + \Delta S$ \hfill (1)

where: $P$ is applied rain [m$^3$], $OF$ is an overland flow [m$^3$] and $\Delta S$ is change in storage over the sprinkling experiment [m$^3$]; $GW_{in}$ and $GW_{out}$ are groundwater inflow and outflow [m$^3$] and are assumed to be equal; $E$ is evaporation [m$^3$] and is neglected as the experimental plots were cover with the tent; $SSF$ is a subsurface flow [m$^3$] and it comprises exfiltration, vertical and lateral flow.

\[ V_T = V_{pre-event} + V_{inf} \]
\[ C_T \cdot V_T = C_{pre-event} \cdot V_{pre-event} + C_{inf} \cdot V_{inf} \hfill (2) \]

where $V_T, V_{pre-event}$ and $V_{inf}$ are respectively the total water volume, the estimated volume of pre-event water and the volume of infiltrated water in [m$^3$]; $C$ is the tracer concentration in [mg m$^{-3}$] and the indexes are analogous to the one used to determine the water volumes.

**Results of Sprinkling Experiments**

Table 1 shows measured components of the water balance and applied tracer concentration for each plot. The summary of observed groundwater variation and tracer concentration patterns is presented in Fig. 3. Results of the three sprinkling experiments show large difference in their hydrodynamic and hydrochemical responses which confirm great variation of hydrogeomorphological properties over the landslide. The general behaviour is in agreement with the one presented by Debieche et al. (2011). The rain water infiltrates into the top soil either through the matrix (plot B) or through both matrix and preferential flow paths (plot A and C). The water flow in the subsurface follows the overall slope direction, however, the presence of fissures and macroporosity (plot A and C) strongly influence the exact direction of the flow.

Based on three experimental plots, three conceptual models of the principal water pathways are formulated:
- Fast vertical flow through the matrix and fissures,
- Matrix flow with limited fissures,
- Isolated fissure system.

**Plot A**

Plot A represents fast input–output type of hydrological response. The system gives very fast response to the rainfall as well as sudden groundwater level drop after rainfall.
Table 1  Measured water balance components for each experimental plot and applied tracer concentrations

<table>
<thead>
<tr>
<th>Day of experiment (tracer)</th>
<th>Plot A</th>
<th>Plot B</th>
<th>Plot C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rain, P [m²]</td>
<td>D1 (Br⁻)</td>
<td>D2 (Cl⁻)</td>
<td>D1 (Br⁻)</td>
</tr>
<tr>
<td>Applied tracers [g m⁻³]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>· Br⁻</td>
<td>0.272</td>
<td>0.332</td>
<td>0.291</td>
</tr>
<tr>
<td>· Cl⁻</td>
<td>118.3</td>
<td>461.3</td>
<td>122.5</td>
</tr>
<tr>
<td>Overland flow, OF [m³]</td>
<td>–</td>
<td>1034.9</td>
<td>–</td>
</tr>
<tr>
<td>Subsurface flow (exfiltration form the fissures) [m³]</td>
<td>–</td>
<td>0.217</td>
<td>0.226</td>
</tr>
</tbody>
</table>

*Exfiltration started after 2 h of sprinkling but was measured only since the third hour.

Fig. 3  Results of three sprinkling experiments: panels (a),(b) and (c) show sprinkling intensity (primary Y-axis) and groundwater level (GWL) responses observed in plot A, B and C (secondary Y-axis); panels (d),(e) and (f) examples of tracer concentrations observed in piezometers A1, B1 and C1 respectively.

is finished. Groundwater level fluctuation in piezometer A1 during the first rain period shows very fast vertical movement of water: both, matrix flow and preferential flow are rapid. High infiltration capacity of the area (>40 mm. h⁻¹, which is the sprinkling intensity), together with surface area characteristics, confirms presence of highly permeable matrix and well connected fissure network. The groundwater behaviour in piezometers A2 and A3 gives an indication of the importance of preferential flow in the area: they suggest the occurrence of faster later flow in the direction indicated by the fissure network and, much slower, matrix flow in a general slope direction.

The mixing process is very clear on plot A. The Br⁻ concentration changes with time show that there is pre-event water in the system that can readily move and 'dilute' the infiltrating water. This high capacity of water remobilization indicates that water is stored not only in the matrix but also has to be stored in macropores (e.g. fissures). After the sprinkling experiment, concentration of the Br⁻ stayed at a high level which confirms that water is (temporarily) stored in the fissures. Within 4 h after the end of the experiment, the system comes back to its initial condition. This clearly indicates that within plot A, hydrological processes are strongly influenced by the system of deep fissures that drains the water out of the experiment area.

Plot B

The general observation of the water balance component (Table 1) indicates that plot B represents matrix behaviour. The relatively low concentration of the tracer in the groundwater can be directly related to the limited infiltration capacity of the area and limited mixing processes. Only 25% of applied water infiltrates into the soil and the majority of the water leaves the system as overland flow. Moreover, the tracer concentrations are relatively low and they remain constant during and after the experiment. This means that there is limited contribution of pre-event water in mixing processes or that not the entire experiment area is hydrologically active. It also indicates low hydraulic conductivity at the deeper layers in the area.

Plot C

The presence of a largely open (up to 0.14 m) fissure system influences distribution of the infiltrating water in the area. The groundwater response and water balance analysis shows that the storage capacity of the area is limited and that hydrological response of the system is a combination of fast vertical infiltration through fissures (surface infiltration)
fast downslope flow (subsurface flow through the fissures), and slow matrix-like flow.

The behaviour of the tracer concentration indicates complex mixing processes in plot C. The relatively low concentration of tracer in piezometer C1 indicates that the significant amount of pre-event water is stored in the matrix but is not mobilised (only 10% of mobile water). The tracer concentration in the subsurface flow is almost the same as the applied initial. It demonstrates that the fissure system is isolated and it provides direct drainage for infiltrated water. The preferential flow occurred through this fissures system is around 50–80% of applied water.

**Discussion and Conclusion**

This paper presents the analysis of three 1 m² sprinkling experiments carried out in the highly heterogeneous mudslide of Super-Sauze. Three hydrological conceptual models of different hydrogeomorphological units are proposed. Presented concepts support the conclusion of Debeche et al. (2011) that landslide body should be seen as double porosity systems, with spatially variable characteristics. They also stress the importance of distributed approaches for forecasting spatiotemporal behaviour of the landslides (e.g.; van Westen et al. 2005; Malet et al. 2005).

In general, the experimental data confirm the advantage of combined hydrological and hydrochemical on-site investigations. They show that small scale sprinkling test can give useful information about the local hydrological system, especially their spatial heterogeneity. As such, they create very good alternative for large scale sprinkling experiments (e.g.; Debieche et al. 2011) that are logistically and financially very demanding and cannot be undertaken on a regular basis.

On going study of the three sprinkling tests include detailed analysis of: tracer mass balance, depletion curve and Darcy’s flow. The next step of this study will be to introduce the concept into a spatially-distributed model coupling hydrological and stability dynamics (van Beek 2002).

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**References**


