

Identifying the origin of groundwater and flow processes in complex landslides affecting black marls: insights from a hydrochemical survey

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Abstract

The Super-Sauze mudslide is a persistently active slow-moving landslide occurring in the black marl outcrops of the French South Alps. It has been intensively studied since the early 1990s. Geotechnical, geomorphological, geophysical and hydrological investigations have led to a better understanding of the processes governing the landslide motion. Water flows inside the system have been proven to have a major impact. To look closer at the processes involved and especially to gain a better idea of the origin and pathways of the waters, a hydrochemical study was carried out from May 2003 to May 2004. The groundwater was sampled during five field campaigns spread uniformly over the year. Groundwater from a network of boreholes was collected as well as spring waters from the fractured bedrock (*in situ* black marl) and from the moraine aquifer above the landslide. Results showed that the groundwater chemistry could not be fully explained by rainfall recharge or simple water–matrix equilibrium. A contribution of saline waters coming from the bottom of a thrust sheet overhanging the landslide was required to get the observed high mineralization. On a flow line, the hydrochemical evolution was related to both soil–matrix equilibrium and deep water sources coming up to the surface by means of major faults, the bedding planes and the schistosity. Hydrochemical anomalies made it possible to point out such contributions locally. It was shown that water chemistry and landslide activity were closely related. This hydrochemical investigation also enabled us to better define the hydrosystem limits. Copyright © 2006 John Wiley & Sons, Ltd.

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Introduction

Hydrological triggering can be considered the most common mechanism of initiation and reactivation of landslides, the stability of which is influenced by non-linear surfaces, subsurface and deep processes that interact across a range of time scales (Montgomery and Dietrich, 1994; Reid, 1997; Ng and Shi, 1998). Fast hydrological processes such as rainfall, surface water flows and infiltration in the subsurface, as well as slow hydrological processes such as deep bedrock flows, control the variations of the groundwater and the development of pressure heads, which is crucial for the interaction of the fluid and the solid phase (Iverson, 2000). A rise in groundwater depth at the slip surface increases pore water pressure and hence decreases the effective shearing resistance of the landslide material. The development of pressure heads is also controlled by the temporal variability of the climatic and precipitation signal; therefore the buffering potential of the unsaturated zone and the hydrological state of the groundwater system are of

paramount importance (Bogaard and Van Asch, 2002). Moreover, the soil mechanics theory postulates that more rainfall must be accumulated to trigger a deep landslide than to trigger a shallow one, all other factors remaining equal (Van Asch *et al.*, 1999).

The variety of landslide types, their size and their more or less complex geological and geomorphological structure create different hydrological systems, which may require the involvement of different hydrological subsystems (Haneberg, 1991; Iverson, 1992, 2000; Bogaard and Van Asch, 2002). A better interpretation of the behaviour of landslides therefore requires various, detailed and interdisciplinary investigations that go far beyond the scope of classic geomorphological, hydrological or geotechnical field and laboratory work (Bogaard *et al.*, 2000; Malet and Maquaire, 2003).

More particularly, little is known about the hydrological system of large, deep-seated and complex landslides which may remain active for long periods (Iverson and Major, 1987; Baum and Reid, 1995; Malet and Maquaire, 2003). Particular attention should be given to the storage and flow of groundwaters within the landslide body, and how they interact with surface waters and intermontane to local stable hillslope aquifers. Hydraulic head data are virtually non-existent for large landslides, and little is known about driving forces such as extreme relief and complex palaeotopography (Iverson and Major, 1987). Hydrologic properties of the landslide material over various scales and the extent to which they are dominated by porous media versus discrete fissure behaviour are also poorly characterized. For instance, fissures opening or clogging due to the soil mass deformation might produce new groundwater pathways and significant changes in cleft water pressures. Moreover, infiltration, circulation depths and residence times of landslide groundwaters are also poorly constrained (Bogaard *et al.*, 2004).

For good prediction of the landslide pore pressure distribution and time delay of the climate input signal, it is necessary to use physically based hydrological models (Iverson and Major, 1986; Van Asch *et al.*, 1999) although they are often restricted to large aquifer properties (area-average values of equivalent parameters) and saturated conditions (Bonomi and Cavallin, 1999; Iverson, 2000). New modelling approaches have recently been developed to account for coupling the saturated and unsaturated zones (Bogaard and Van Asch, 2002; Van Beek and Van Asch, 2004), for the spatial variability of the material properties (Miller and Sias, 1998), or for simulating the effects of preferential water flows (Malet *et al.*, 2005). However, some physical processes and the boundary conditions of the systems are not well constrained by these types of model. Identifying the origin of groundwater in the landslide body and the flow processes is thus an essential step forward in enhancing the concept of the physically based models already used (Corominas, 1998; Bogaard *et al.*, 2004). As landslide concepts are very often inferred solely from hydrological data, hydrochemistry can be used to trace the origins and history of groundwater (Appelo and Potsma, 1993).

In the last decade, several attempts to use geochemical information for landslides studies have been made through hydrochemical analyses of spring waters (Figure 1), for example as at La Clapière landslide (Guglielmi *et al.*, 2002a; Cappa *et al.*, 2004), Séchilienne landslide (Guglielmi *et al.*, 2002b), Hohberg landslide (Tullen, 2002), La Valette

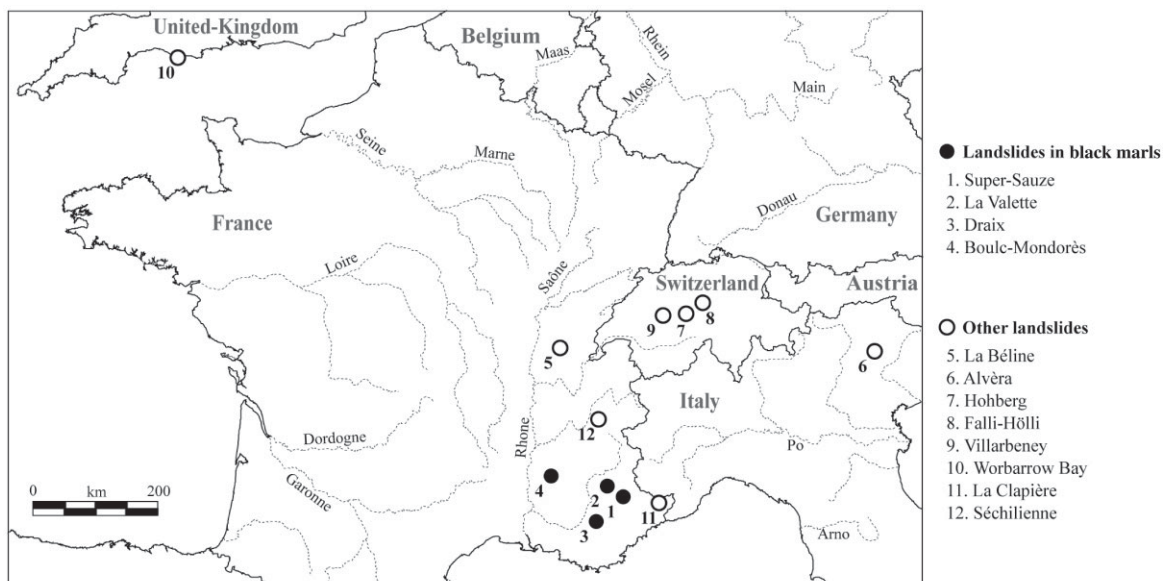


Figure 1. Location of the European landslides where hydrochemical investigations have been performed in the last decade and location of the landslides developed in the black marls of the French South Alps.

landslide (Le Mignon, 2004) and Villarbene and Falli-Höllli landslides (Oswald, 2003). Cation exchange capacity analyses of landslide groundwaters have also been made, for example at Worbarrow Bay landslide (Moore and Brunsten, 1996) and at La Beline, Alvera and Boulc-Mondorès landslides (Bogaard *et al.*, 2000, 2004). These studies concluded that hydrochemistry and geochemistry are potentially valuable techniques for providing indications for zones that are important for shallow and deep-seated landslides, such as slip surfaces or preferential flow tracks, but recognized that a lot of work still has to be done before the techniques can be applied in engineering practice. These previous hydrochemical studies were carried out from spring water sampling which provided a spatially integrated approach for the processes. In this study, the investigation was performed using a network for boreholes and piezometers, so we also obtained spatially distributed information on water flow and water pathways.

This paper focuses on the hydrochemical part of an interdisciplinary study of slow-moving mudslides in the French South Alps. The main objectives of the study were twofold: (a) to investigate the potential of hydrochemical techniques to determine the origin of the water for large and deep-seated clay-rich landslides, and to define the boundary conditions of the landslide complexes; (b) to improve our knowledge on the hydrological short- and long-term evolution of such intra-material landslides using hydrochemical information.

The Study Site: Morphodynamic Setting of the Complex Super-Sauze Mudslide

The research focuses on the hydrological behaviour of the Super-Sauze mudslide, one of the persistently active landslides (since the 1970s) occurring in black marls (Malet and Maquaire, 2003).

The geological environment is very complex and is the consequence of the geological history of this alpine zone characterized by an overthrust of allochthonous sandstone and limestone formations over the autochthonous black marl bedrock (Figure 2a, b). From the highest to the lowest elevations, the geological levels comprise (Figure 2b):

- the dominantly calcareous Klippe of Lan (Figure 2a, c) which overhangs the mudslide and gives evidence of the Parpaillon thrust sheet revealed by erosion processes; the Parpaillon thrust sheet has moved during the lower and mid-Eocene with the help of gypsum layers acting as 'soap' layers (Figure 2b);
- the moraine (3 to 15 m thick) deposited by the Ubaye glacier during the Quaternary age (Figure 2b);
- the autochthonous bedrock consisting of Callovo-Oxfordian black marls (Figure 2b), which present a grey clayey schist facies, very finely laminated and highly tectonized (Maquaire *et al.*, 2003).

The landslide was triggered at the beginning of the 1970s at the interface between the moraine and the autochthonous black marls by using the different discontinuities (fault, bedding plane, joint and schistosity) affecting the bedrock. The mudslide material consists of a silty-sand matrix mixed with moraine debris. It extends over a horizontal distance of 850 m and occurs between an elevation of 2105 m (crown) and 1740 m (toe) with an average 25° slope. A detailed morphological description of the mudslide since its genesis can be found in Weber and Herrmann (2000). The palaeotopography, corresponding to a succession of more or less parallel crests and gullies, plays an essential role in the behaviour of the landslide by delimiting preferential water and material pathways and creating sections with differing kinematic, mechanical and hydrological characteristics. The total volume is estimated at 750 000 m³ and velocities range from 0.01 to 0.4 m.day⁻¹. The mudslide is bordered by two lateral gullies with perennial run-off and characterized by a central gully with intermittent run-off.

Its geotechnical structure (Figure 3) consists of two superimposed units (Flageollet *et al.*, 1999; Malet and Maquaire, 2003). The upper unit, 5 to 9 m thick, is a very wet, muddy formation, which can be subdivided into two subunits (C1a and C1b). This unit is very active from a hydrological and mechanical view point. The lower unit, with a maximum thickness of 10 m, is a stiff, compact, relatively impervious and apparently stable formation (Malet *et al.*, 2002).

Field and Laboratory Methods

The landslide hydrology and kinematics have been monitored since 1996 and a spatio-temporal database on rainfall, temperature, capillary pressure head, soil moisture content, groundwater level and displacement is available (Malet, 2003; Malet *et al.*, 2005). Around 20 open standpipe piezometers with manual recordings, filtered at different levels, are distributed over the landslide body (Figure 4a).

Water sampling campaigns were carried out in 2003 (May, July and October) and 2004 (April and May). Each time, groundwater was sampled from seven to ten piezometers. The sampling was completed with surface water collected in the most upstream gully in the black marl (UG) and with spring waters coming from the moraine aquifer located

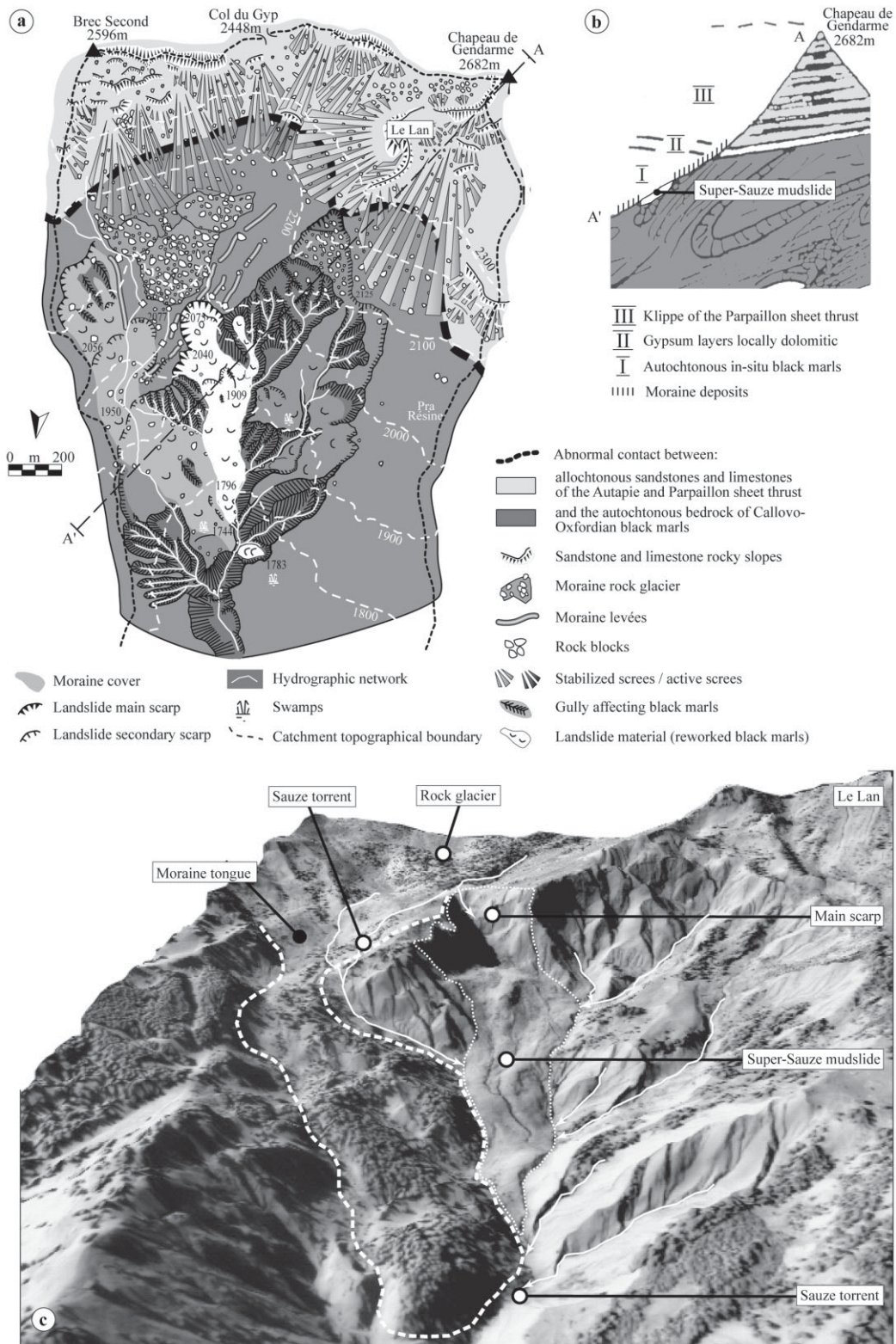


Figure 2. Geological and geomorphological setting of the Super-Sauze mudslide. (a) Geomorphology of the Super-Sauze catchment. (b) Schematic geological cross-section of the catchment. (c) 3D view of the catchment reconstructed from a pair of aerial photograph of 1995.

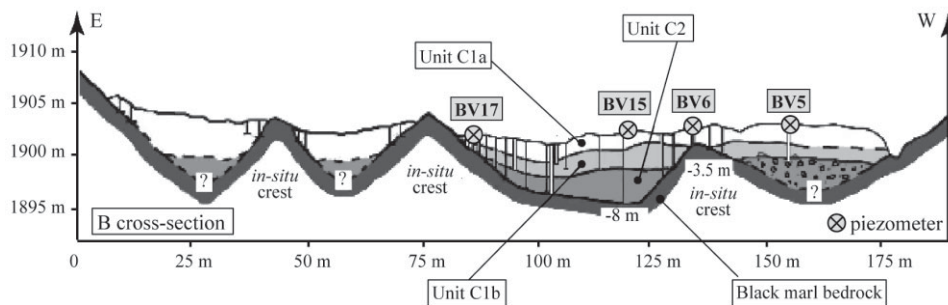


Figure 3. Geotechnical structure of the mudslide on the B cross-section and location of piezometers.

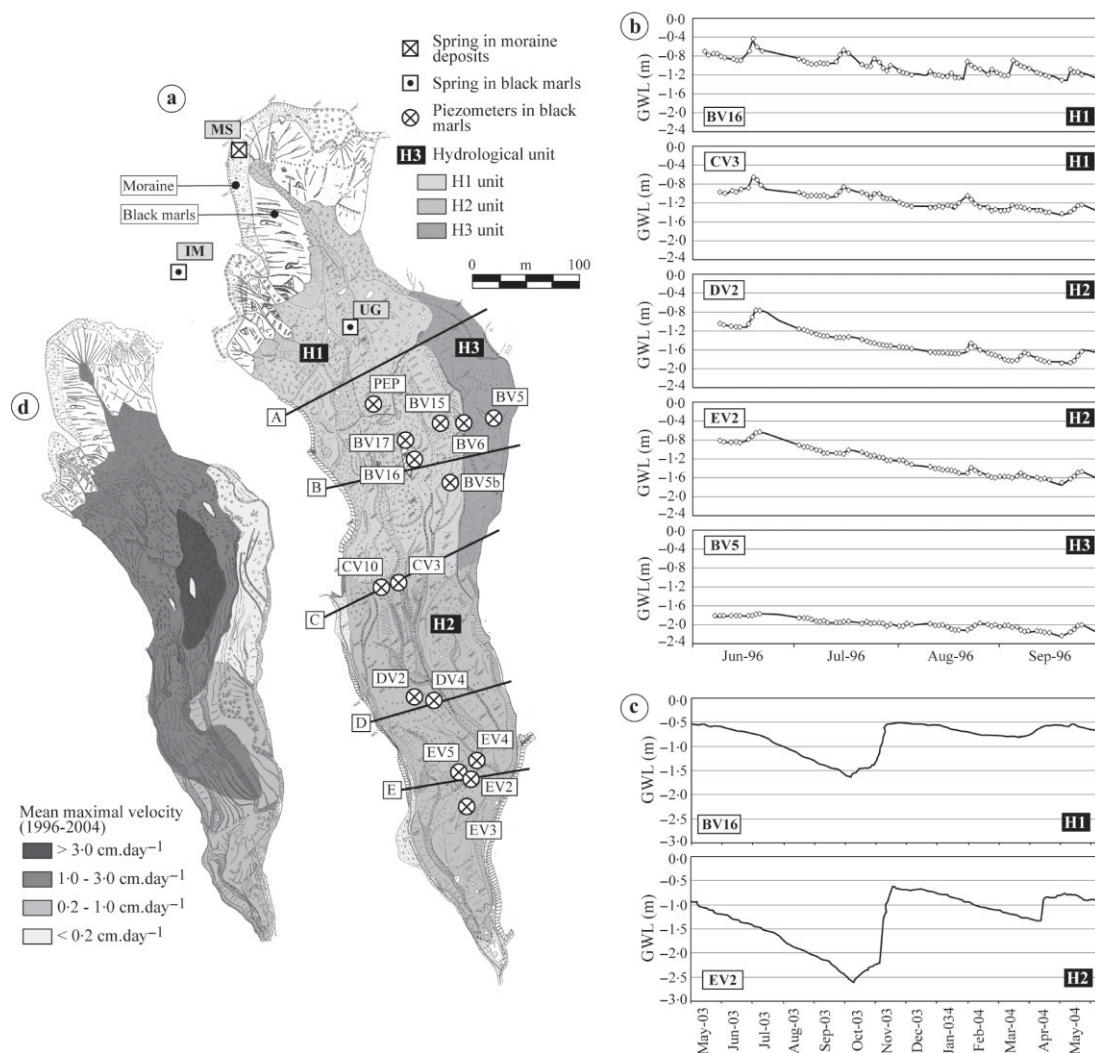


Figure 4. Hydrology and kinematics of the mudslide. (a) Geomorphological map, location of the piezometers surveyed and identification of the hydrological units. (b) Example of short-term variation (3 months, daily manual recording) of the groundwater (June 1996–September 1996). (c) Example of long-term variation (1 year, 10 minutes automatic recording) of the groundwater (May 2003–May 2004). (d) Velocity map (mean maximal daily velocities observed on the mudslide from 1996 to 2004).

above the mudslide (MS) and from the *in-situ* marl (IM). For a short-term investigation at a critical recharge period (snowmelt in spring), a daily sampling of groundwater was also performed on the B cross-section during three weeks in April and May 2004.

Direct measurements of water temperature, electrical conductivity EC, acid potential pH, redox potential EH and total alkalinity TA were performed on the field. All water samples were collected in polyethylene bottles and filtered through a 0.45- μm membrane. Analyses of major and minor cations (calcium Ca^{2+} , magnesium Mg^{2+} , sodium Na^+ , potassium K^+ , iron Fe^{2+} , strontium Sr^{2+}) and major anions (chloride Cl^- , sulphate SO_4^{2-} , nitrate NO_3^-) were carried out with atomic absorption spectrometry and liquid phase ionic chromatography, respectively. Ca^{2+} analyses were performed by adding lanthanum chloride in the water samples to prevent any atomic interference. This technique is known to provide accurate results on low-mineralized waters. The total relative uncertainty, including the device accuracy and the repeatability error, is known to be less than 5 per cent for all compounds. Nevertheless, except for the moraine waters, the high-mineralized waters of the mudslide had to be diluted up to a factor of 100. The mean total uncertainty including the additional error due to this dilution procedure can then be estimated at 10 to 15 per cent for the dominant species (SO_4^{2-} , Ca^{2+} , Mg^{2+}) and less than 10 per cent for the other compounds.

Landslide Groundwater Hydrology

Previous studies (Malet, 2003; Malet *et al.*, 2005) allowed three hydrological units to be distinguished on the basis of short- and long-term groundwater fluctuations and of morphological features.

- (i) The upstream H1 unit (A to C cross-section) is characterized by large groundwater variations at the event time scale and relatively medium variations at the yearly time scale (± 0.5 – 1.0 m). Bypass processes through the crack system preferentially occur in these areas.
- (ii) The downstream H2 unit is characterized by lower short-term variations but higher seasonal variations (± 0.1 – 2.5 m) than for the first unit. In this case, recharge mainly occurs with slow infiltration processes through the matrix porosity. This analysis is in keeping with the geomorphological observations which indicate that the cracked surface layer has a limited extension in the D cross-section and is not present in the E cross-section (although a major crack system has recently appeared on the latter).
- (iii) In the H3 unit, situated in the western part of the mudslide, both short- and long-term groundwater variations are very low.

Figure 4b and c compare the short-term and long-term groundwater fluctuations for the different units. Hence the recharge conditions proved to be very different whether the observation is made upstream or downstream, involving different hydrological subsystems and some spatial correlations with the activity of the mudslide (Figure 4d). A joint analysis of all geological, geomorphological, geotechnical and hydrological data acquired since 1996 resulted in a hydrological concept of the mudslide (Malet *et al.*, 2005). Within this concept, the recharge of the system is mainly attributed to rainfall events (at the end of spring and at the beginning of autumn) as no other information was available. The rapid piezometric responses are due to infiltration processes controlled both by fast preferential vertical flows through a shallow system of interconnected cracks and by slower matrix flows. An upstream surface flow from the *in-situ* marls or the moraine aquifers is supposed to contribute to the yearly recharge of the landslide but is not expected to explain the event-scale piezometric responses. Vertically, the system is limited by the impervious unit C2 (Figure 3) while the two lateral gullies with perennial run-off are considered as the lateral boundary limits. Therefore the hydrological system is defined as the extent of the mudslide without any deep contribution.

The hydrological concept includes three layers. The upper one with permeable crack system overlies two layers with lower permeability values due to compaction. Rapid vertical flows through the cracks occur at the surface, then slower processes arise below where infiltration is dominated by matrix flow. Although the mudslide presents a continuous and unconfined aquifer in its major part, field observations showed that it could be confined in some places and even artesian (water level was sometimes measured above the soil). Pumping tests carried out in five of the available piezometers have also shown lateral variations of the hydrological settings. Transmissivity values were calculated from the recovery curve after cessation of pumping using the Jacob semi-log time drawdown method (Fetter, 1994). The results ranged between 5×10^{-6} and $10^{-5} \text{ m}^2 \text{ s}^{-1}$ and are of the same order of magnitude as those measured by Malet *et al.* (2005), though slightly greater. Also, the landslide material heterogeneity resulted in lateral variations of the hydrologic properties.

Clearly this hydrological concept has several assumptions that arise from knowledge limited to classic geomorphological, geotechnical and hydrological investigations, and which can benefit from further refining.

Table I. Mineralization in the groundwater of the Super-Sauze mudslide

Value (meq l ⁻¹)	SO ₄ ²⁻	Ca ²⁺	Mg ²⁺	Na ⁺	HCO ₃ ⁻	Cl ⁻	K ⁺	Sr ²⁺
Mean	37.48	15.32	21.17	6.01	4.95	0.06	0.30	0.05
Min.	4.77	3.44	2.24	0.21	1.35	0.01	0.06	0.01
Max.	76.57	30.12	40.43	35.03	10.50	0.38	0.89	0.12

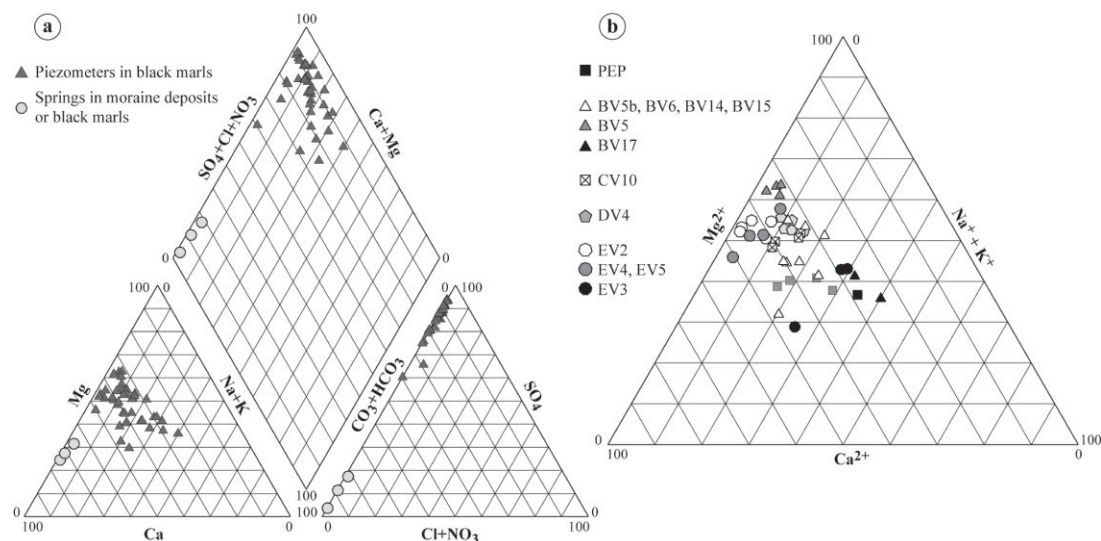


Figure 5. Chemical values of waters from the Super-Sauze catchment represented as percentage of total milliequivalents per litre on the trilinear diagram originated by Piper. (5) Cation and anion variations for groundwater and surface water. (b) Enlargement of cation variations for the landslide groundwater.

Landslide Water Chemistry

Mineralogical properties of the black marls

The mineralogy of the black marls has been investigated by Phan (1993), Schmutz (2000) and Maquaire *et al.* (2003). The analysis of the <2- μ m fraction has been carried out using X-ray diffractometry on oriented paste. The samples were taken on the B cross-section at a depth ranging from 0.5 to 6 m. All results give a nearly equal ratio of carbonates (calcite, dolomite), silicates (quartz, albite) and phyllosilicates (clays). The mean composition is clays (40 per cent), quartz (25 per cent), calcite (25 per cent), dolomite (5 per cent), plagioclase (3 per cent) and pyrite (2 per cent). The *in-situ* marl and the landslide material have similar mineralogical content. The clay fraction is composed of illites (80 per cent), chlorites (20 per cent) and some traces of smectites (Maquaire *et al.*, 2003). Pyrite was mainly observed as vein-shaped minerals which can explain the content variation (0.9 to 4.2 per cent) from one sample to another. Qualitatively, the large quantity of observable pyrite on the site suggests that the mean content of 2 per cent is underestimated. Sulphuric acid as a pyrite oxidation product may contribute to the rock decarbonation and gypsum formation. This situation is not observed here. Indeed, Schmutz (2000) showed that there is no gypsum in the mudslide material.

General hydrochemical features and origins of water

Table I and Figure 5 depict the relative abundance of ions in individual water samples taken from the piezometers in the landslide material or from springs issuing from the moraine or *in-situ* black marl above. The diagram shows that the most abundant anion in the mudslide groundwater is SO₄²⁻ while HCO₃⁻ is dominating in the moraine waters (Figure 5a), as also observed at Boulc-Mondores landslide (Bogaard *et al.*, 2000, 2004). Ca²⁺ is the major cation in the moraine waters. The water sampled in the mudslide has a higher concentration of Mg²⁺ than Ca²⁺ and some samples

Table II. Chemical values (in meq l⁻¹) of groundwater in some landslides developed in marls of southeast France

Location	Rock type	SO ₄ ²⁻			Ca ²⁺			Mg ²⁺			Na ⁺		
		Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.
Valette	Callovo-Oxfordian marls	27.3	9.5	48.3	29.8	10.6	56.7	19.6	3.2	34.9	2.1	0.04	9.7
Draix	Callovo-Oxfordian marls	7.8	0.8	22.2	4.8	1.2	11.2	4.4	0.8	10.2	1.1	0.1	4.2
Boulc	Callovo-Oxfordian & Aptian marls	18.0	15.6	19.7	2.4	1.2	3.71	1.3	0.8	1.6	30.2	28.1	31.6

Data regarding Valette, Draix and Boulc are respectively from Le Mignon (2004), Cras (2005) and Bogaard *et al.* (2000).

are marked by relatively high abundance of Na⁺ (Figure 5b). The waters from the mudslide are strongly mineralized (Table I). The total ionic concentration may reach 177 meq l⁻¹ with an EC ranging from 1500 µS cm⁻¹ to over 6000 µS cm⁻¹. In contrast, the moraine waters do not exceed a total charge of 7 meq l⁻¹ with a mean EC of 290 µS cm⁻¹.

If compared with hydrochemical data from other landslides in marls of the southern French Alps the waters from the Super-Sauze mudslide appear to be much more mineralised (Table II). The main difference concerns SO₄²⁻, the concentration of which can be up to twice that observed in the other studies. Another point is that unlike most landslides situated in black marls where Ca²⁺ is usually the dominant cation, Mg²⁺ was found to be the major cation in the Super-Sauze mudslide. Lastly, the specificity of the Super-Sauze mudslide lies in the very high Na⁺ concentrations (up to 35 meq l⁻¹) which balance the negative charges supplied by the extra SO₄²⁻ ions.

This abundance of ions does not correspond to the chemical features of detritic carbonate formations (Meybeck, 1984). It suggests an evaporitic origin. However, for sulphates, pyrite oxidation should not be excluded even though it is considered as a minor mechanism. In such a way, strontium analyses were carried out to further investigate the evaporitic impact upon the water chemistry. According to Meybeck (1984), high strontium concentrations (median up to 120 µeq l⁻¹) are explained by the celestite dissolution which is usually associated with gypsum. The waters sampled at the Super-Sauze mudslide range between 11 and 116 µeq l⁻¹ with a mean value of 52 µeq l⁻¹. Furthermore, Sr²⁺/Ca²⁺ ratios (expressed in mol l⁻¹) higher than 1 per mil are characteristic of evaporitic waters (Meybeck, 1984; Hsissou *et al.*, 1996). At Super-Sauze, this ratio ranges between 1.2 and 7.8 per mil, clearly arguing for an evaporitic origin of the waters. In this context, the high Na⁺ concentration of the waters has a saline origin. The imbalance between sodium and chloride is explained by the high mobility of chloride whilst sodium is easily adsorbed on the soil matrix. The high proportion of Mg²⁺ is also due to dissolution of salts. In most carbonate environments, the magnesium concentration of waters is constrained by the dissolution of dolomite which is less soluble than calcite, so that the magnesium content is usually far lower than the calcite content. Though they are of saline origin, these constituents are also strongly constrained by the processes of precipitation–dissolution of carbonate minerals. Figure 6a and b show respectively the saturation of waters for the calcite and the dolomite minerals. Most of the samples are in equilibrium or oversaturated with respect to both minerals. The wide range of computed partial pressure of CO₂ in the atmosphere (pCO₂) is also indicative of the variations of the flow conditions throughout the mudslide. All the situations in between are observed from the highest pCO₂ found for the deep, long-residence-time waters to the near-surface waters in equilibrium with the atmosphere.

Geochemical modelling

As a further investigation into the origin of the waters, a geochemical modelling exercise was performed to check whether the water chemistry in the landslide could be deduced from the mineralogy of the landslide material. The thermodynamic- and kinetic-based model KINDIS (Madé *et al.*, 1990) has been used to simulate the observed water concentrations according to different water–rock interactions. This model describes the interactions between minerals and aqueous solutions taking into account the irreversible dissolution of reactants and the reversible precipitation of secondary products. Evolution of the chemical composition of the solution and distribution of the elements between simple and complex ions are also determined. KINDIS calculates, for steady-state equilibrium, the quantity of destroyed or formed phases per kilogram of water, according to the reaction rate which corresponds to the mass of dissolved rock per kilogram of weathering solution. The kinetic part of the modelling study was not performed here due to the lack of major parameters regarding several constituents such as contact surfaces or kinetic constants. The model was

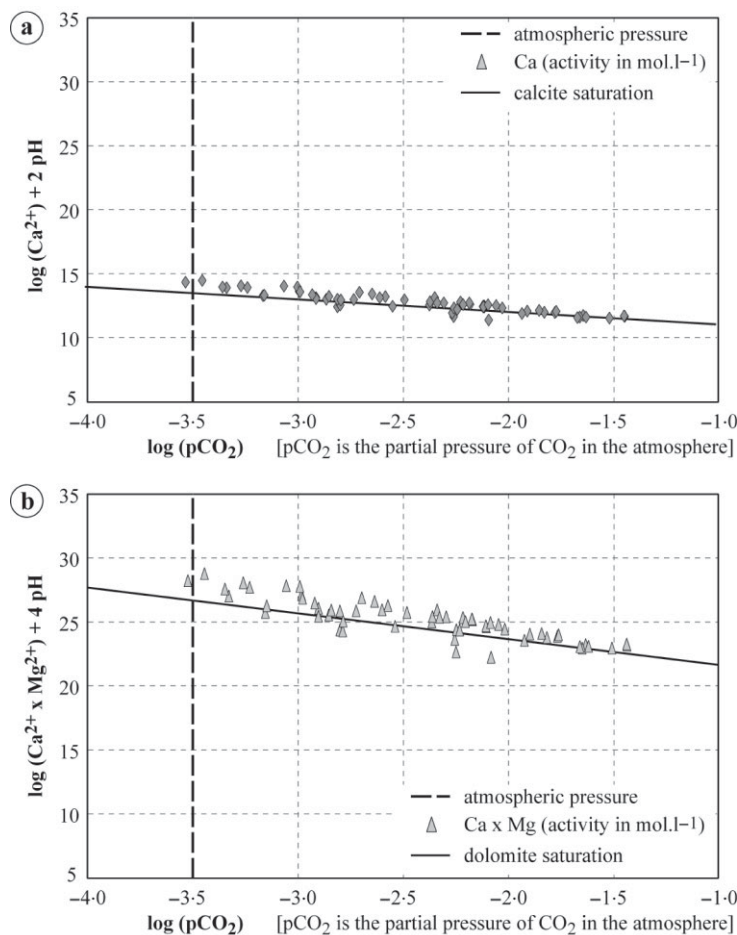


Figure 6. Precipitation–dissolution processes of carbonates expressed in terms of partial pressure of CO₂ in the atmosphere. Precipitation–dissolution diagram of (a) calcite and (b) dolomite.

Table III. Input chemical values (in mg l⁻¹) of the waters tested in the KINDIS model

Spring/piezometer	Code	T (°C)	pH	SO ₄ ²⁻	HCO ₃ ⁻	Cl ⁻	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺
Moraine spring	MS	–	7.3	20.4	121.7	0.4	34.8	10.1	1.8	nd
<i>In-situ</i> black marl spring	IM	6.4	8.1	109.9	195.2	0.5	74.3	29.2	3.3	0.7
Upstream gully	UG	8.5	7.8	551.0	322.7	0.3	110.0	89.6	144.9	6.0
Landslide piezometer	PEP	–	7.2	1030.0	417.0	0.4	161.0	124.0	206.0	11.0
	CV10	–	7.2	1953.0	365.0	0.7	290.0	271.0	142.0	12.0

–, data unavailable; nd, species not detected at the analysis.

used to assess the chemical saturation level of the different minerals by performing iterative computations until the system has reached equilibrium between the mineral phases and the water.

Several scenarios were tested according to the chemical composition of the input water (moraine, *in-situ* black marl, surface water from the upstream gully UG) and the abundance of some minerals described above. The objective was to fit the theoretical composition of water with the mean chemical composition measured in the piezometers PEP and CV10 (Figure 4a). The first step consisted in running the model in order to get a SO₄²⁻ concentration of about 1000 mg l⁻¹, then computations of Ca²⁺, Mg²⁺, Na⁺ and HCO₃⁻ were performed to fit as closely as possible with the observed values. The chemical features of the input waters are summarized in Table III.

The main results of the simulations are described in Table IV. By using the moraine water (MS) composition as input data, it was possible to get the required SO_4^{2-} concentration with pyrite oxidation as the only process (Table IV, Test 1). However, the pH attained a lower value than expected while saturation was reached for calcite and dolomite, so that Ca^{2+} and Mg^{2+} concentrations did not rise enough. The observed SO_4^{2-} concentration was also obtained with water originating from the *in-situ* black marl spring (IM). But, as for the previous case, saturation for dolomite was rapidly attained preventing the Mg^{2+} concentration from increasing. The case of Na^+ was not settled whatever the scenario used. Indeed, in assuming albite as the only Na^+ supplier, it was not possible to gain enough Na^+ because albite saturation was attained too rapidly (Table IV, Tests 2 and 3). Only the surface water from the upstream gully (UG) led to a final chemical composition close enough to the observed values (Table IV, Test 4). Indeed, the UG water should not be considered as a true input of the landslide hydrological system as it was sampled on the landslide about 50 m down the main scarp.

These results indicate that the mudslide water chemistry cannot be explained by the dissolution of the constituent material. Water is clearly not originating from rainfall with subsequent enrichment or from any other sources detected in the field. Evaporites, which are not present in the mudslide material, have been proved to be the only origin of the observed water chemistry. These points stress the major impact of the gypsum and dolomite layer of the overthrust contact of the klippe of Lan, which is the only identified source of evaporite at a regional scale. This contact is located far beyond the Super-Sauze catchment. However, aerial photographs prove that a complex fault system beneath the Lan could provide salt-enriched waters (Figure 2a, b).

Spatial distribution of the chemical species

The variation of water chemistry in the mudslide retained the same features for all the sampling campaign (Figure 7).

From the PEP piezometer in the upstream part of the landslide, there was a systematic increase of the water mineralization downwards (Figure 7a, b), while the proportion of Na^+ decreased (30 to 5 per cent) for the benefit of Ca^{2+} and Mg^{2+} (30 to 50 per cent and 35 to 60 per cent, respectively). Several processes can explain the general hydrochemical features along the flow line: a decrease of the water dilution processes downstream (mixing of the landslide groundwater with the low mineralized moraine waters or rainfall waters); dissolution–precipitation of carbonate minerals; cation exchange on the clay minerals which mostly involves an increasing concentration of Ca^{2+} and Mg^{2+} while the Na^+ concentration decreases (Figure 7b) (isomorphic exchange between Ca^{2+} and Mg^{2+} cannot be excluded either); or pyrite dissolution.

Looking closely at the chemical variations along this flow line (Figure 8), the concentrations of major ions rose rapidly from PEP to CV10, then slowed down to the E cross-section. Meanwhile, the strontium concentration, after a first step of increase like the other ions, started to decrease from the C cross-section. This behaviour suggests that SO_4^{2-} is first related to evaporites; then pyrite dissolution as an intra-source of SO_4^{2-} induces a second stage of SO_4^{2-} increase.

There was evidence that the upstream–downstream water chemistry evolution could be explained not only by the processes cited above. The problem arose with the Mg^{2+} whose concentration should be constrained by the dolomite solubility and should not reach such high values (Table IV). As only an out-of-catchment magnesium salt such as kieserite (MgSO_4) could provide enough Mg^{2+} , a deep source of water is expected. This potential source of water cannot be deduced from classic geotechnical or hydrological investigations. This deep contribution was locally pointed out in the B cross-section. Indeed, in the BV17 piezometer (Figure 4a), the water was more highly mineralized than expected and showed the greatest abundance of Na^+ . This piezometer is situated in the most active part of the mudslide (Figure 4d) in the vicinity of an *in-situ* crest (Figure 3). Deep salt-water is then assumed to come up to the surface along discontinuities affecting the bedrock. On the western part of the B cross-section, the piezometer BV5 is split from the other piezometers by a second *in-situ* crest (Figure 3). Its water was found to be less mineralized but with a higher proportion of magnesium. The chemistry of this water indicates that the recharge occurs locally without any high contribution of deep highly mineralized water. Assuming no significant impact of the waters from the evaporites, the high magnesium content is explained by a long residence time of waters in the mudslide carbonate environment. These results are in keeping with the observation that this sector is a stable, nearly motionless part of the mudslide.

Long- and short-term time variation of the chemical species

Long- and short-term variations of the hydrochemistry were surveyed to investigate further the conditions of subsurface water infiltration. Comparison between chemical variations and hydrologic observations was expected to provide arguments upon the distribution of rapid preferential vertical flows and slow matrix flows. On the C cross-section,

Table IV. Results of the geochemical simulations (in mg l⁻¹)

Water tested	MPM	PM	SM	Simulated values*		Comments
				PEP	CV10	
T1	MS	Pyrite	Illite, montmorillonite, calcite, kaolinite, siderite, amorphous silica	pH = 6.8 SO ₄ ²⁻ = 1079 Mg ²⁺ = 159 Ca ²⁺ = 49 HCO ₃ ⁻ = 38	–	It is possible to increase SO ₄ ²⁻ in spite of the beginning of acidification. But calcite and dolomite are saturated.
T2	IM	Pyrite	Calcite, siderite, kaolinite	pH = 7.5 SO ₄ ²⁻ = 1106 Mg ²⁺ = 144 Ca ²⁺ = 264 Na ⁺ = 7.9	–	Albite is the only source of Na ⁺ and is too quickly saturated.
T3	IM	Pyrite = 5% Albite = 5% Quartz = 20%	Calcite, siderite, kaolinite	pH = 7.5 SO ₄ ²⁻ = 1068 Mg ²⁺ = 158 Ca ²⁺ = 227 Na ⁺ = 9.5	–	Albite is the only source of Na ⁺ and is too quickly saturated. Mg ²⁺ cannot rise because the dolomite is already saturated.
T4	UG	–	Siderite, kaolinite	pH = 7.1 SO ₄ ²⁻ = 1000 Mg ²⁺ = 109 Ca ²⁺ = 292 Na ⁺ = 145	pH = 6.9 SO ₄ ²⁻ = 1530 Mg ²⁺ = 109 Ca ²⁺ = 420 Na ⁺ = 145	It is possible to find the same order of magnitude as the PEP concentrations but not the CV10 concentrations because the dolomite is already saturated (even if the percentage of dolomite is raised until to 15%).
T5	UG	Kisierite = 2% Quartz = 23%	Siderite, kaolinite	pH = 6.9 SO ₄ ²⁻ = 711 Mg ²⁺ = 122 Ca ²⁺ = 175 Na ⁺ = 144	pH = 6.9 SO ₄ ²⁻ = 1886 Mg ²⁺ = 220 Ca ²⁺ = 460 Na ⁺ = 145	It is possible to find the same order of magnitude as the PEP and CV10 concentrations.

MPM, modified primary minerals; PM, primary minerals which can dissolve in the range of the observed sulphate values; SM, secondary minerals which precipitate in the range of the observed sulphate values;

* Simulated values to be compared with the measured values in Table III.

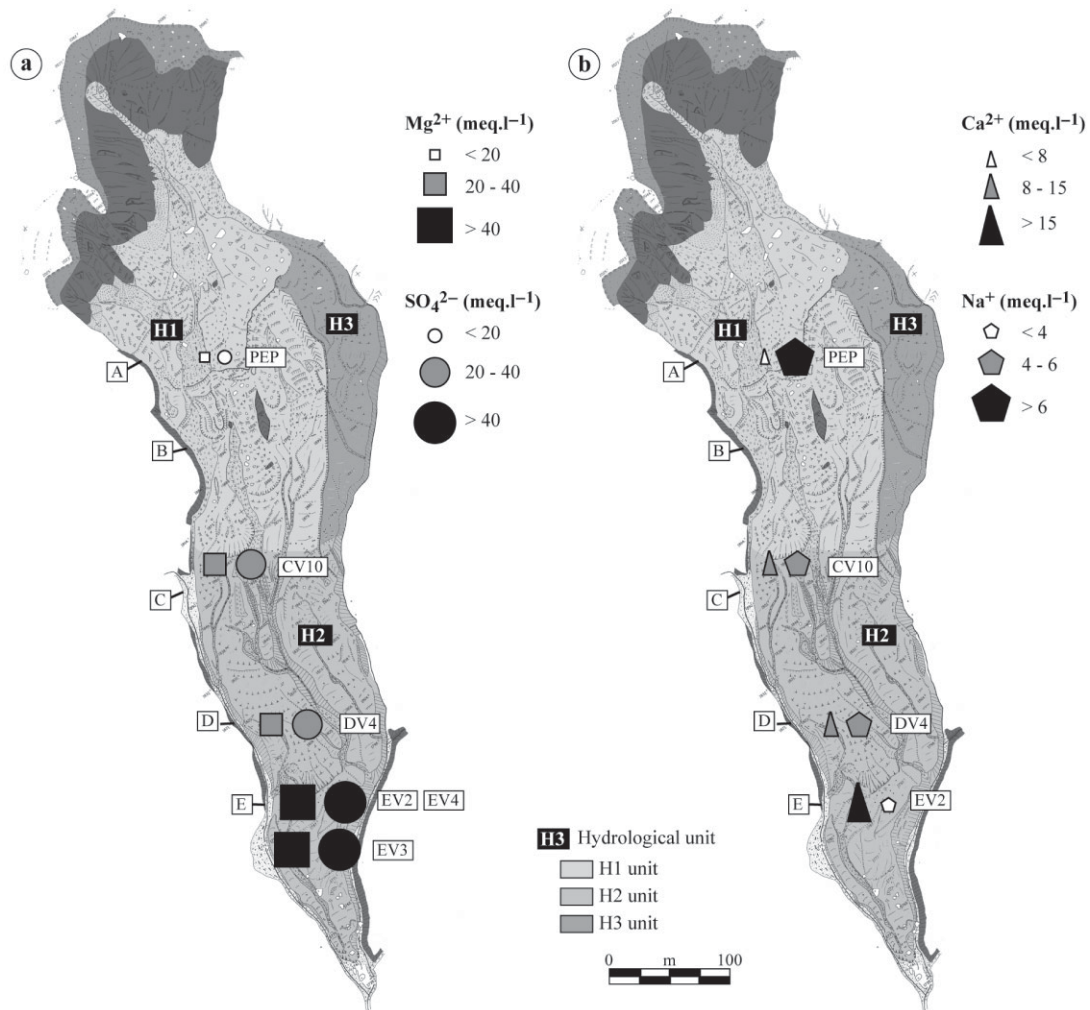


Figure 7. Spatial distribution of the major cations and anions. (a) Variation of groundwater chemistry along a flow line. (b) Process of Ca²⁺-Na⁺ exchanges along a flow line.

only low seasonal chemical variations were observed in agreement with the steady groundwater level (Figure 9a). This result confirms that this unit is not influenced by slow infiltration through the soil matrix. Infiltration processes take place using the cracks network. The cracks clog as soon as the landslide material is sufficiently re-wetted, so they have only a short-term impact on the water chemistry, as well as on the groundwater variations.

On the D and E cross-sections, similar hydrologic behaviour was observed, though very different chemical variations. After the rainfall of autumn 2003, the concentrations slightly decreased on D and rose on E after a sharp drop. The groundwater variation was also more pronounced in the case of unit E. The recharge of the aquifer on both units is thus pointed out with a dilution effect generated by the new water infiltration. The higher reactivity on unit E (for both chemistry and groundwater) is due to a newly formed major crack system which was observed on the field for different soil moisture conditions. As these cracks were still developing, they did not close up and they were expected to speed up the vertical water flows as well as enhance the drainage (as can be observed on the groundwater recordings). Another consequence was a major dilution effect which was observed just before the rise of the water table and should have been amplified onwards. Unfortunately, the sampling time step did not enable us to make a more detailed analysis of the infiltration conditions.

The short-term chemical variations were investigated in April and May 2004, at the beginning of the snow-melt period. A large amount of snow fell in 2004, inducing a thick snow cover reaching a maximum thickness of 2.1 m on the B cross-section. Water was sampled using an automatic sampler from the piezometer BV5b at a daily time step

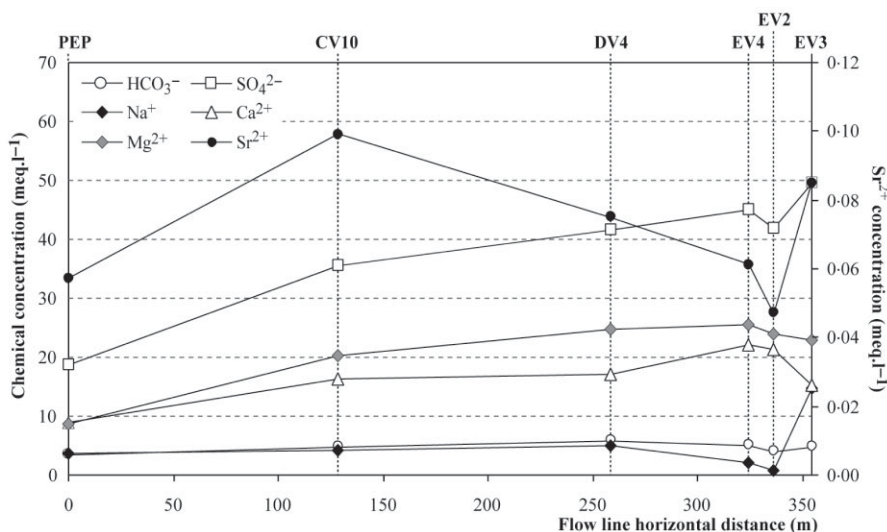


Figure 8. Hydrochemical variations of the major cations and anions along a flow line.

from 22 April 2004 to 11 May 2004. The sampler was covered with glass wool and a plastic sheet to prevent water losses by evaporation and frost during the nights. As the water is usually in equilibrium or oversaturated with respect to carbonates, precipitation of calcite or dolomite could have occurred in the sampling bottles. The similar behaviour between carbonate species and the other elements shows that, if carbonate precipitation occurred, it was of minor extent (Figure 10).

All the ions except NO_3^- were characterized by the same variation. After a first period of increase, the concentrations dropped to a minimum value measured on 5 May before rising again. This evolution is a good illustration of the infiltration and recharge processes. The first part of the increasing concentrations is explained by the contribution of the pre-event soil water which reached the groundwater via a piston flow mechanism. As soon as the low-mineralized new water has reached the water table, the concentrations decreased as a consequence of the dilution effect. The new water is enriched in nitrate compared with the pre-event water, as a result of cattle or other animals' faeces lying on the ground surface. As melting and water sampling started at the same time, it was possible to assess the mean transit time of water infiltrating through the unsaturated zone. With a value of about 7 days deduced from the Figure 10, the preferential vertical flows are confirmed to be of major importance on this unit.

A Conceptual Model of Flow Processes and Waters Origin

This hydrochemical investigation allowed refinement of the conceptual hydrological model of the mudslide as proposed by Malet *et al.* (2005). Water chemistry has shown that rain waters and moraine aquifers were not the only input components. The evidence of an evaporitic origin involves a contribution of areas outside the catchment limits. Salt-enriched waters are then expected to come from the overthrust contact of Lan via a complex fault system. The impact of these waters has been identified as near the upper boundaries as in the piezometer PEP, proving that an inflow occurs far upstream.

As an example of a deep water contribution, peculiar geochemical behaviour has been observed on the B cross-section (BV17). Unexpectedly high concentrations of SO_4^{2-} in this part of the mudslide are indicative of deep inflow. Such a deep water source is not surprising considering the regional fault system context and the highly tectonized features of the marl bedrock (Malet *et al.*, unpublished work). The piezometer is situated on the edge of an *in-situ* crest very close to the bedrock outcrop. Water can easily move along the major discontinuities (faults, bedding planes and schistosity) up to the surface. It is interesting to note that this particular zone around piezometer BV17 is considered as the most active part of the mudslide (Figures 4d and 11).

From an input of highly mineralized water, the intra-system geochemical variation is also explained by complex processes including mixing with moraine waters, dissolution–precipitation of carbonates, pyrite dissolution and cation exchange. At a shorter time step, recharge by new water occurs with slow or rapid vertical transfer according to the unit where the infiltration takes place.

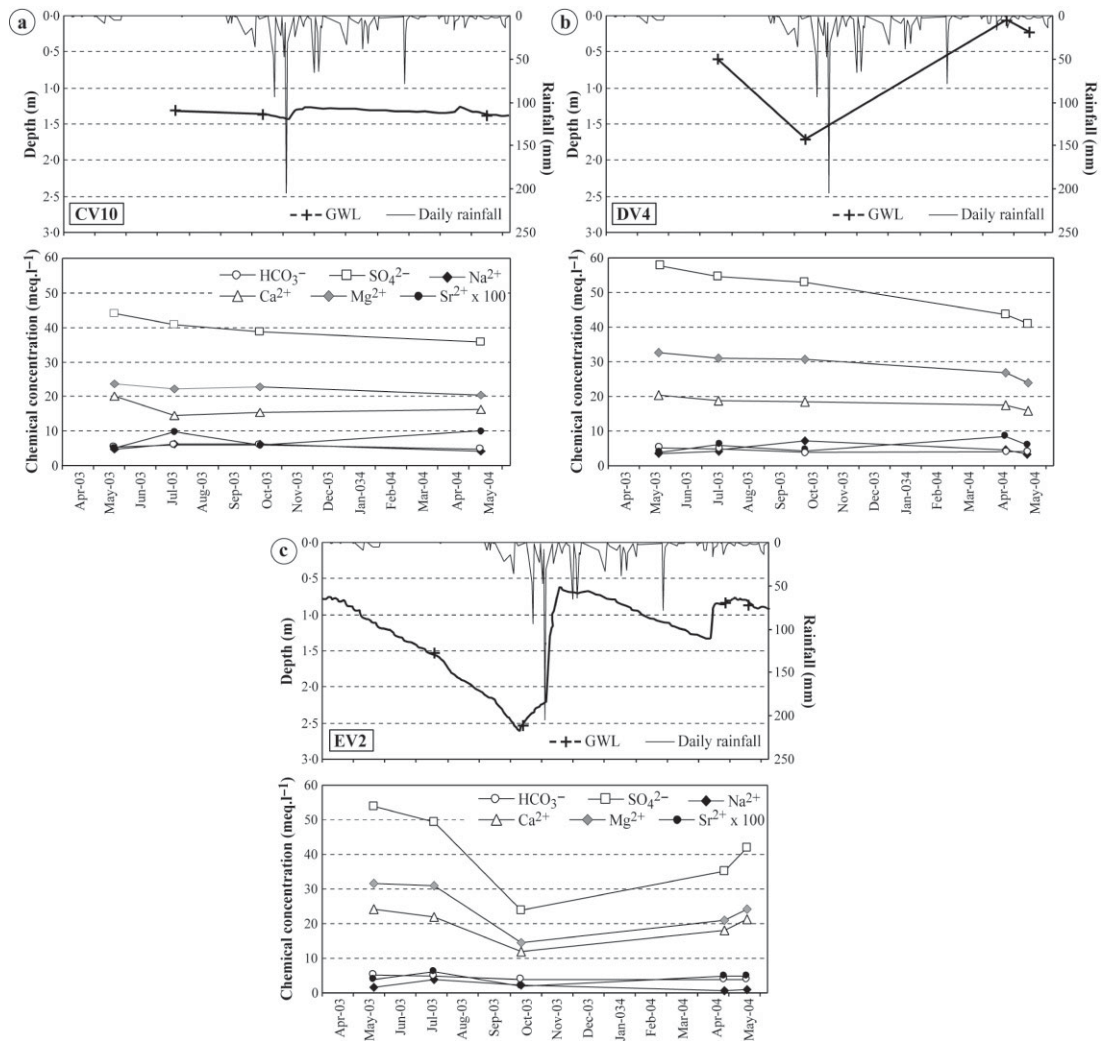


Figure 9. Long-term (seasonal) hydrochemical variations compared with the groundwater variations: (a) on the C cross-section; (b) on the D cross-section; (e) On the E cross-section.

Other studies have also demonstrated the influence of physico-chemical processes of water on the stability of clay soils. For example, Moore (1991), Moore and Brunsten (1996) and Di Maio (1996) have shown that the ionic strength of the pore water had a direct impact on the strength of Van der Waals bonding within the diffuse double layers between clay mineral layers. Dilute solutions are expected to weaken the Van der Waals forces and make the clay particles unstable. Conversely, residual cohesion will be more effective and clay soils will be more stable when the concentration of water is high. In our case, the relation between water chemistry and landslide motion is not that straightforward since the concentration of water may vary with time according to the relative impact of deep, highly mineralized waters, of surface moraine water or of rainwater with lower concentration. The breakdown of materials in the unstable part of the landslide may promote infiltration through the cracks and may result in accelerating the landslide movement. But this effect is compensated by the impact of water with a high concentration which results in an improvement in landslide stability by promoting Van der Waals attractive forces between clay mineral layers. Besides this physico-chemical effect, a continuous flow of water at the basal part of the landslide should play a key role in the mechanics of the system.

Although it is still not easy to split the relative role of each of these processes, the connection between water chemistry and landslide activity is highlighted by comparing the mapped chemical properties and the landslide velocity (Figures 4d and 11). It is then shown that the upslope part of the landslide where the water has a high concentration (especially Na⁺, Mg²⁺ and SO₄²⁻) is also the most active part.

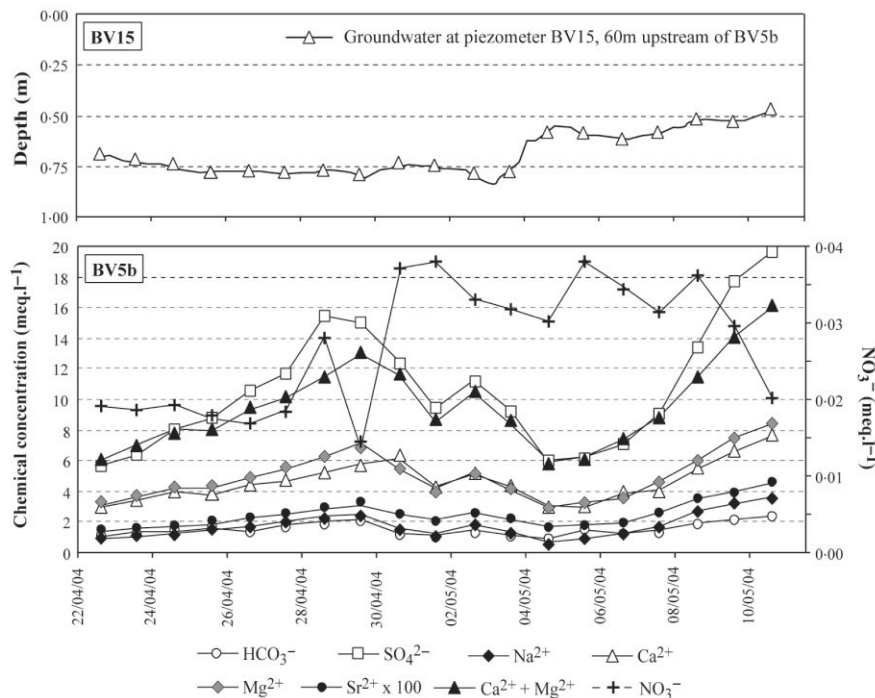


Figure 10. Short-term chemical variations at BV5b piezometer compared with the groundwater variations at BV15 piezometer.

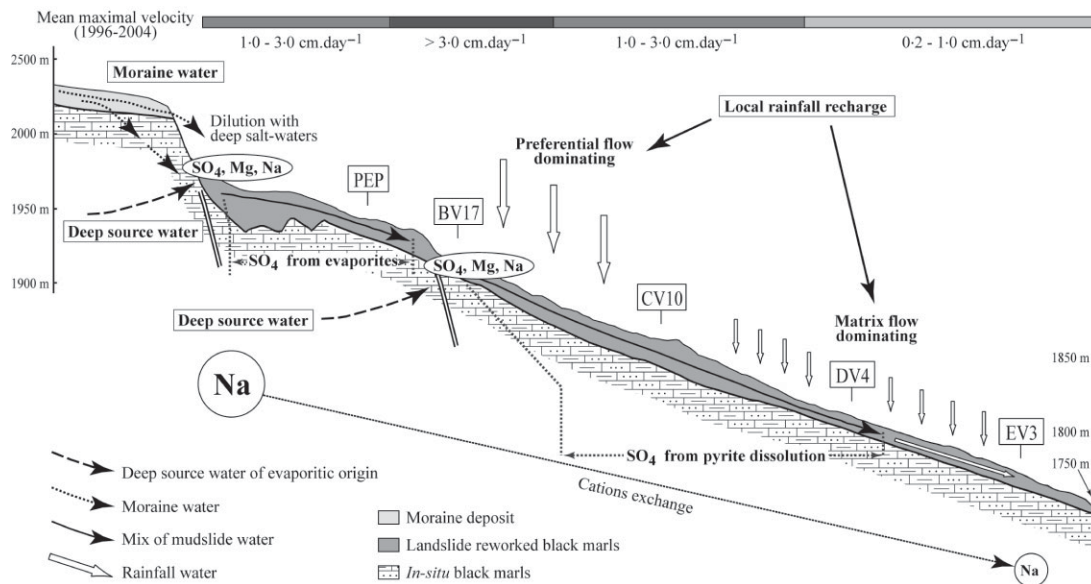


Figure 11. Synthetic scheme representing the hydrological concept of the Super-Sauze mudslide as interpreted from hydrochemical analyses, with indication of the mudslide velocities.

Conclusion

A preliminary hydrochemical investigation of the Super-Sauze mudslide allowed us to specify some points regarding the water flows circulating inside the hydrological system. It was shown that the limits of the hydrological system could be extended to the overthrust contact of the klippe of Lan located beyond the Super-Sauze landslide. This deep

origin of water has a hydrochemical consequence since it provides a very high mineralization to the input water and is expected to create weaker zones inside the landslide material. Rainfall and subsurface waters circulating in the moraine deposits are the two other origins of water. The chemical contrast between the rainwater or moraine water and the salt-water from the klippe of Lan may partly explain the temporal variation of the landslide movement. A decrease of the pore-water concentration (e.g. influence of rainfall and moraine water infiltration) would result in a reduction of the clay effective cohesion while a high concentration would improve landslide stability. The expected correlation between groundwater chemistry and landslide activity has been pointed out in the field. The active zone of the landslide has been shown to have high concentrated water with a particular anomaly in the Na⁺ concentration.

Nevertheless, many questions related to the water pathways are still to be settled. The improvement of our knowledge regarding the processes involved requires a further investigation into the water chemical enrichment. For this, a detailed chemical analysis of the black marl is required to go further with the geochemical modelling and to take into consideration the kinetic processes. This analysis, combined with isotopic investigations, is of prime importance since it will be needed to quantify the relative contribution of the different water sources. This knowledge is a key point for performing suitable long-term hydrological modelling

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References

- Appelo CAJ, Postma D. 1993. *Geochemistry, Groundwater and Pollution*. Balkema: Rotterdam.
- Baum RL, Reid ME. 1995. Geology, hydrology, and mechanics of a slow-moving, clay-rich landslide, Honolulu, Hawaii. *Reviews in Engineering Geology, Geological Society of America* **X**: 79–105.
- Bogaard TA, Van Asch ThWJ. 2002. The role of the soil moisture balance in the unsaturated zone on movement and stability of the Beline landslide, France. *Earth Surface Processes and Landforms* **27**: 1177–1188.
- Bogaard TA, Antoine P, Desvarreux P, Giraud A, Van Asch ThWJ. 2000. The slope movements within the Mondorès graben (Drôme, France); the interaction between geology, hydrology and typology. *Engineering Geology* **55**: 297–312.
- Bogaard TA, Buma JT, Klawer CJM. 2004. Testing the potential of geochemical techniques for identifying hydrological systems within landslides in partly weathered marls. *Geomorphology* **58**(1–4): 323–338.
- Bonomi T, Cavallin A. 1999. Three-dimensional hydrogeological modelling application to the Alverà mudslide (Cortina d'Ampezzo, Italy). *Geomorphology* **30**(1–2): 189–199.
- Cappa F, Guglielmi Y, Soukatchoff VM, Mudry J, Bertrand C, Charvoille A. 2004. Hydromechanical modeling of a large moving rock slope inferred from slope levelling coupled to spring long-term hydrochemical monitoring: example of the La Clapière landslide (Southern Alps, France). *Journal of Hydrology* **291**: 67–90.
- Corominas J. 1998. *New technologies for landslide hazard assessment and management in Europe*. EC-Programme NEWTECH ENV-CT96-0248. European Commission: Brussels.
- Cras A. 2005. *Etude de la dynamique de fonctionnement hydrologique des bassins versants torrentiels marneux. Apport du traçage naturel*. Doctoral Thesis, University of Avignon and Pays de Vaucluse, Avignon.
- Di Maio C. 1996. The influence of pore fluid composition on the residual shear strength of some natural clayey soils. In *Proceedings of the 7th International Symposium on Landslides*, Seneset K (ed.). Balkema: Rotterdam; 1189–1194.
- Fetter CW Jr. 1994. *Applied Hydrogeology* (third edition). Prentice-Hall: New York.
- Flageollet J-C, Malet J-P, Maquaire O. 1999. The 3D structure of the Super-Sauze earthflow: a first stage towards modelling its behaviour. *Physics and Chemistry of the Earth* **25**(9): 785–791.
- Guglielmi Y, Bertrand C, Compagnon F, Follaci J-P, Mudry J. 2002a. Acquisition of water chemistry in a mobile fissured basement massif: its role in the hydrogeological knowledge of the La Clapière landslide (Mercantour massif, southern Alps, France). *Journal of Hydrology* **229**(3–4): 138–148.
- Guglielmi Y, Vengeon J-M, Bertrand C, Mudry J, Follacci J, Giraud A. 2002b. Hydrogeochemistry: an investigation tool to evaluate infiltration into large moving rock masses (case study of La Clapière and Séchillienne alpine landslides). *Bulletin of Engineering Geology and the Environment* **61**(4): 311–324.
- Haneberg WC. 1991. Pore pressure diffusion and the hydrologic response of nearly saturated, thin landslide deposits to rainfall. *Journal of Geology* **99**(8): 886–892.
- Hsissou Y, Chauve P, Mania J, Mangin A, Bakalowicz M, Gaiz A. 1996. Caractérisation des eaux de l'aquifère turonien du bassin du Tadla (Maroc) par le rapport des concentrations molaires Sr²⁺/Ca²⁺. *Journal of Hydrology* **183**: 445–451.

- Iverson RM. 1992. Sensitivity of stability analyses to groundwater data. In *Proceedings of the 6th International Symposium on Landslides*, Bell DH (ed.). Balkema: Rotterdam; 451–457.
- Iverson RM. 2000. Landslide triggering by rain infiltration. *Water Resources Research* **36**(7): 1897–1910.
- Iverson RM, Major JJ. 1986. Groundwater seepage vectors and the potential for hillslope failure and debris flow mobilization. *Water Resources Research* **22**: 1543–1548.
- Iverson RM, Major JJ. 1987. Rainfall, ground-water flow, and seasonal movement at Minor Creek landslide, northwestern California: physical interpretations of empirical relations. *Geological Society of America Bulletin* **99**: 579–594.
- Le Mignon G. 2004. *Analyse de scénarios de mouvements de versants de type glissements-coulées. Application à la région de Barcelonnette (Alpes de Haute Provence, France)*. Doctoral thesis, Ecole Nationale des Ponts et Chaussées, Paris, France.
- Made B, Clement A, Fritz B. 1990. Modélisation cinétique et thermodynamique de l'altération: le modèle géochimique KINDIS. *Comptes-Rendus de l'Académie des Sciences, Série II* **310**: 31–36.
- Malet J-P. 2003. *Les 'glissements de type écoulement' dans les marnes noires des Alpes du Sud. Morphologie, fonctionnement et modélisation hydro-mécanique*. Doctoral thesis, University Louis Pasteur, Strasbourg.
- Malet J-P, Maquaire O. 2003. Black marl earthflows mobility and long-term seasonal dynamic in southeastern France. In *Proceedings of the International Conference on Fast Slope Movements: Prediction and Prevention for Risk Mitigation*, Picarelli L (ed.). Patron Editore: Bologna; 333–340.
- Malet J-P, Maquaire O, Calais E. 2002. The use of Global Positioning System techniques for the continuous monitoring of landslides: application to the Super-Sauze earthflow (Alpes-de-Haute-Provence, France). *Geomorphology* **43**(1–2): 33–54.
- Malet J-P, Van Asch ThWJ, Van Beek R, Maquaire O. 2005. Forecasting the behaviour of complex landslides with a spatially distributed hydrological model. *Natural Hazard and Earth System Science* **5**: 71–85.
- Maquaire O, Malet J-P, Remaître A, Locat J, Klotz S, Guillon J. 2003. Instability conditions of marly hillslopes: towards landsliding or gullying? The case of the Barcelonnette Bassin, South East France. *Engineering Geology* **70**(1–2): 109–130.
- Meybeck M. 1984. *Les fleuves et le cycle géochimique des éléments*. Doctoral thesis, University Pierre et Marie Curie, Paris.
- Miller DJ, Sias J. 1998. Deciphering large landslides: linking hydrological groundwater and stability models through GIS. *Hydrological Processes* **12**: 923–941.
- Montgomery DR, Dietrich WE. 1994. A physically-based model for the topographic control on shallow landsliding. *Water Resources Research* **30**(4): 1153–1171.
- Moore R. 1991. The chemical and mineralogical controls upon the residual strength of pure and natural clays. *Géotechnique* **41**(1): 35–47.
- Moore R, Brunsden D. 1996. Physico-chemical effects on the behaviour of a coastal mudslide. *Geotechnique* **46**(2): 259–278.
- Ng CWW, Shi Q. 1998. A numerical investigation of the stability of unsaturated soil slopes subjected to transient seepage. *Computers and Geotechnics* **22**(1): 1–28.
- Oswald D. 2003. *Analyse de l'activité de glissements de terrain et relation avec les conditions climatiques: exemple dans les Préalpes fribourgeoises (Suisse)*. Doctoral thesis, University of Fribourg, Fribourg.
- Phan TSH. 1993. *Propriétés physiques et caractéristiques géotechniques des Terres Noires du Sud-est de la France*. Doctoral thesis, University of Grenoble.
- Piper AM. 1944. A graphic procedure in the geochemical interpretation of water analyses. *Trans. Amer. Geophys. Union* **25**: 914–923.
- Reid ME. 1997. Slope instability caused by small variations in hydraulic conductivity. *Journal of Geotechnical and Geoenvironmental Engineering* **123**: 717–725.
- Schmutz M. 2000. *Apport des méthodes géophysiques à la connaissance des glissements-coulées développés dans les marnes noires. Application à Super-Sauze (Alpes-de-Haute-Provence, France)*. Doctoral thesis, University Louis Pasteur, Strasbourg.
- Tullen P. 2002. *Méthodes d'analyse du fonctionnement hydrogéologique des versants instables*. Doctoral thesis, Swiss Federal Institute of Technology, Lausanne.
- Van Asch ThWJ, Buma J, Van Beek LPH. 1999. A view on some hydrological triggering systems in landslides. *Geomorphology* **30**: 25–32.
- Van Beek LPH, Van Asch ThWJ. 2004. Regional assessment of the effects of land-use change on landslide hazard by means of physically-based modelling. *Natural Hazards* **31**(1): 289–304.
- Weber D, Herrmann A. 2000. Contribution de la photogrammétrie numérique à l'étude spatio-temporelle de versants instables; l'exemple du glissement de terrain de Super-Sauze (Alpes-de-Haute-Provence, France). *Bulletin de la Société Géologique de France* **171**(6): 637–648.