Prediction of changes in landslide rate induced by rainfalls: from the use of a black box model to a 1D mechanical model

Séverine Bernardie, Nicolas Desramaut, G. Russo, J. Zurcher, Gilles Grandjean

Prediction of changes in landslide rate induced by rainfalls: from the use of a black box model to a 1D mechanical model

S. Bernardie, N. Desramaut, G. Russo, J. Zurcher, G. Grandjean
BRGM, Orléans France

ABSTRACT: This study focuses on an innovative methodology to predict landslide accelerations, based on a black box tool and a 1D mechanical model to predict the evolution of the daily displacements according to the variations of precipitation. More specifically, the impulse response model allows to predict the changes in the landslide rate by computing the transfer function between the input signal (precipitation in this case) and the output signal (the displacements). The second model uses a simple 1D mechanical model, with considering a viscoplastic behavior of the landslide, and with taking into account the evolution of the pore water pressure.

These methods have been applied to the Super-Sauze landslide, which takes place in the Southern French Alps, mountainous region. This site is controlled by the active movement within black marls, with velocities ranging between 0.002 and 0.4 m per day. The results show that the snowmelt has to be taken into account in the models, since the phenomena of freezing /thawing has an influence on the water refills, leading to changes in the movement. The approaches are compared and their complementarity is demonstrated in this study. It results in the development of a methodology for predicting changes in landslide rate based on criteria of comparison between the observed and calculated velocities. The results suggest that the impulse response model reproduces the observed data with very good accuracy, whereas the mechanical model seems to be more adapted to predict the movements within 10 days. Moreover, the RMSE criterion permits to highlight the occurrence of the flow, with considering all models, 11 days before the flow itself.

1 INTRODUCTION

Predicting landslides is a challenge for scientists, as it may help save lives and protect individual properties or collective resources. One of the main challenges in active landslide monitoring concerns the prediction of slope's movements in the near future. This study focuses on an innovative method to predict landslide accelerations, by using statistical analyses of various data acquired in situ and a 1D mechanical model. Most of the instrumentation systems designed for monitoring landslides induced by rainfalls are basically based on measurements of water pressure, displacement and precipitation.

More specifically, two methods are proposed to predict the evolution of the daily displacements of the movement according to the variation of precipitation. The first one concerns a black box tool, TEMPO software (Pinault and Schomburgk, 2006), which allows to predict the changes in the landslide rate by computing the transfer function between the input signal (precipitation in this case) and the output signal (the displacements). This function is based on impulse response functions. The second approach uses a simple 1D mechanical model, which considers a viscoplastic behavior of the landslide.

Both methods have been applied to the Super-Sauze landslide, which takes place in the Southern French Alps, mountainous region. This site is controlled by the active movement within black marls, with velocities ranging between 0.002 and 0.4 m per day. Approaches are compared and their complementarity is analysed.

2 THE LANDSLIDE AREA: THE SUPER-SAUZE MUDSLIDE

The studied landslide is located in the French south Alps in the Barcelonnette Basin, on the left bank of the Ubaye River. The Super-Sauze landslide is a continuously active mudslide, within the Callovian-Oxfordian black marls. The mudslide extends over a horizontal distance of 850 m, and occurs between an elevation of 1740m and 2105m with an average slope of 25°. The total volume is estimated at 750 000 m^3.

From a hydrological and geotechnical viewpoint, the mudslide is structured in two vertical units: the first unit (5 to 10 m thick) is a moderately stiff and semi-permeable material, while the second unit (with a maximum thickness of 10 m) is a stiff and impervious material (Malet and Maquaire, 2003). Both materials involve low plasticity, intensely fissured reworked black marls with a sandy-silt matrix.

Deformation occurs as a consequence of a rise of the perennial groundwater table, resulting in the development of positive pore pressures in the moving material. Groundwater fluctuations are controlled by water infiltration both in the soil matrix and in large kinematical cracks and fractures as well as recharge from the torrents bordering the landslide (Malet *et al.*, 2005; de Montety *et al.*, 2007).

The contact between the active mudslide and the stable hillslopes comprises a shearing zone of a few meters width characterized by tension cracks.

For the 1996-2004 period, the velocity of the landslide lies in the range from 0.002 to 0.03 $m.day^{-1}$. Landslide crises have also been observed, with velocity up to 0.4m. day^{-1}. In particular, a large flow occurs on October 31st, 2006, which will be analyzed in the present study.

This site is well instrumented with long temporal series (up to ten years of data), measuring the displacements, the piezometers, and precipitations.

The precipitations are recorded as total daily precipitation (either rainfall or snowfall). The maximum observed daily precipitation for the 1996-2004 period reaches 81.4 mm/day, and the yearly summation has high variability, ranging from 540 mm/year to 935 mm/year

3 IMPULSE RESPONSE MODEL

The impulse response model (IR model) is based on a global approach based on the use of a black box model. It is derived from TEMPO software (Pinault and Schomburgk, 2006), originally dedicated to hydrogeological and hydrogeochemical data analysis. It permits to process data and model temporal series, with computation of transfer functions between input data and output data, based on signal process methods, inversion and optimization technics.

More precisely, this model reproduces an output signal S using convolution product of an input signal E by a transfer function G as described in the equation (1). This function is based on impulse response functions.

$$S(n.dt) = G * E(t) = \sum_{i=1}^{k} G(i.dt).E((n-i+1).dt) \qquad (1)$$

where n = the discretized interval time, and k = the order (length) of the impulse response.

The shape of the transfer functions chosen in this study is a convolution of a Gaussian function by an exponential function.

Moreover, as the Super-Sauze landslide is located in a mountain context with the occurrence of snow, the snowmelt has to be taken into account.

Several models more or less complex exist to simulate the melting snow (Kustas, 1994). The one used in this model is based on simple parameters, such as the critical temperature Tc, permitting to establish the limit between rain and snow within the measured precipitations; the coefficient a, estimates the rate of snow melting per day and per degree, as described in the equation:

$$\text{snowmelt} = a.\,(T(t) - Tc) \quad \text{if } T(t) > Tc \qquad (2)$$
$$\text{snowmelt} = 0 \quad \text{if not}$$

4 VISCOPLASTIC SLIDING 1D MODEL

A 1D infinite viscous model is considered from Herrera et al. (2009). In this approach, the model assumes a pre-existing slip surface, above which the sliding mass moves as a rigid body. It considers a viscoplastic behavior of the landslide. The landslide is assumed to be a translational infinite slide with constant depth h and constant slope a.

It takes directly into account the daily effective rainfall intensity (rainfall and snowmelt, as defined in paragraph 3) and the dissipation of the excess pore-fluid with using a simple consolidation equation.

The momentum balance equation can be written over the slope direction as:

$$\tau - c + \sigma n - Pw\ t\ .\tan\varphi = m.a\ t + \frac{\eta}{d} v(t) \quad (3)$$

where τ = the destabilizing shear stress; σ_n = normal stress; ϕ = friction angle; c = cohesion ; m = mass of the landslide; η = viscosity; d = thickness of the shear zone; $p_w(t)$ = pore water pressure; a(t) = acceleration and v(t) = velocity.

With the assumptions of flow parallel to the slope surface, the pore water pressure is defined as:

$$p_w = z\ t\ \gamma_w . cos^2 \alpha \quad (4)$$

where z(t) = position of the groundwater level and γ_w = specific weight of water. Changes in groundwater level have been taken directly proportional to the effective rainfall intensity:

$$dz = I_{rainfall}/1000/n \quad (5)$$

where $I_{rainfall}$ = effective rainfall in mm/m²/day and n = porosity.

The dissipation of the excess pore water pressure in the saturated layer is governed by the Terzaghi's one dimensional consolidation theory, as described in the following relationship:

$$ep_w = ep_{w0} . \mathrm{e}^{-t/Tv} \quad (6)$$

where ep_{w0} = initial excess pore water pressure and T_v = time factor controlling the dissipation time of the excess pore pressure defined as:

$$Tv = \frac{4H^2}{\pi^2 Cv} \quad (7)$$

where c_v = consolidation coefficient.

Prediction of the displacement is obtained by solving the equation 1, with using optimized functions, permitting to optimize some geometry parameters (h and d), and some material properties (ρ, ϕ, η, n and T_v parameters).

5 RESULTS

5.1 Comparison between the models

The models have been first applied to the data acquired on the Super-Sauze site from 14/12/2005 to 21/08/2006. The length of the calibration period is 100 days. The Figure 1 and Figure 2 highlight the performances of the models with the following criteria: Nash and RMSE (Root Mean Square Error). The performances of the calibrations depend on the period. Some tests have also demonstrated that the calibrations depend on the size of the windows.

We can see that the impulse response (IR) model provides variable but generally good accuracy with Nash values ranging from 0 to 0.94 and RMSE values lying between 0.0015 and 0.008 m.day^{-1}. Various tests have been conducted to improve this model, with addition of input data, such as Evapotranspiration, the delay due to snowmelt, the separation between rainfall and snowmelt, and the streamflow of Ubaye River. The model obtained with the best accuracy is the one with snowmelt contribution separated from the rainfall (considering two impulse responses).

The 1D hydromechanical viscoplastic (VP) model also provides good results, with Nash values ranging from 0.04 to 0.94 and RMSE between 0.0016 and 0.008 m.day^{-1}.

In this study, another model has also been tested (IR_VP): this model mixes the two previous ones, with a first step linking the precipitations and the ground water level with an impulse response model, and then the 1D mechanical model between the water level and the displacements. The results are surprisingly not as good as it could be supposed, with Nash values ranging from -0.4 to 0.5 and RMSE comprise between 0.002 and 0.008 m.day^{-1}.

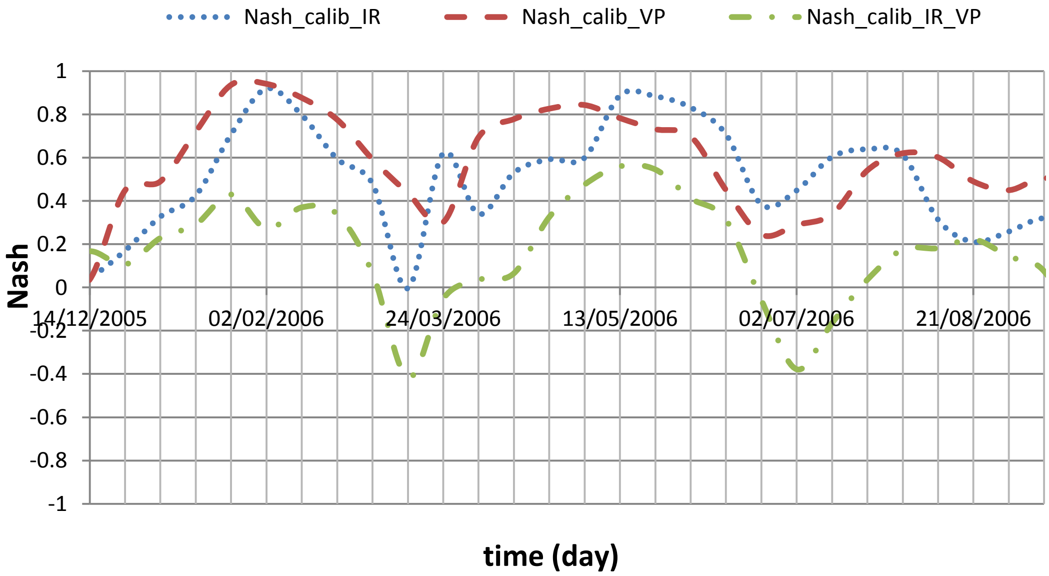

Figure 1 - Nash criterion for the IR, VP and IR_VP models – 14/12/2005 to 10/10/2006

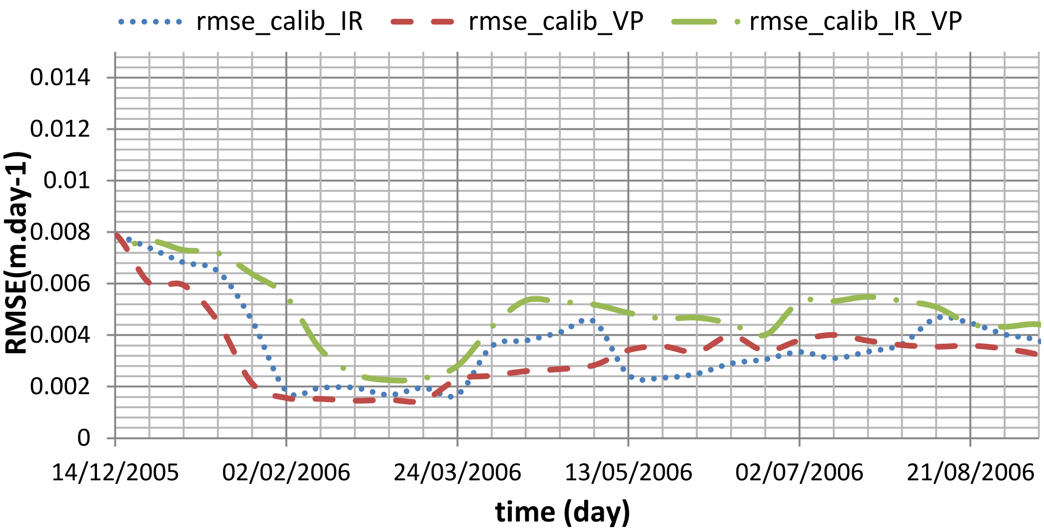

Figure 2 - RMSE criterion for the IR, VP and IR_VP models – 14/12/2005 to 10/10/2006

5.2 Calibration of the models

The three models have then been applied to the whole period, from 01/01/1999 to 31/11/2010. After realizing some tests, we obtain the calibrated model with the best accuracy with considering a shifted calibration window of 100 days.

Concerning the viscoplastic model, the parameters are optimized within the following range values:

a = 25 °; c = 0 kPa; ϕ = [11-25]° ; ρ = [1600-2400] kg.m^{-3} ; η = 4.9 10^{E6} Pa.s; n = [0.01 – 0.6]; T_v = [1-139] days; d = [0.1 – 0.7] m; h = [8 -10] m.

The Figure 3 shows the computed and observed displacements, as well as the precipitations during this period. We observe that the three models fit well the observed data, with a Nash criteria of 0.32 for VP model, 0.26 for IR model, and 0.15 for IR_VP model. The RMSE computed for all this period is of 0.004 m.day^{-1} for IR and VP models, and 0.005 m.day^{-1} for IR_VP model.

The impulse response model slightly underestimates the observations, whereas the viscoplastic model, as well as the impulse reponse- viscoplastic model, slightly overestimate the measured displacements. Moreover, we can observe that the IR model reproduces more finely the local variations of displacements.

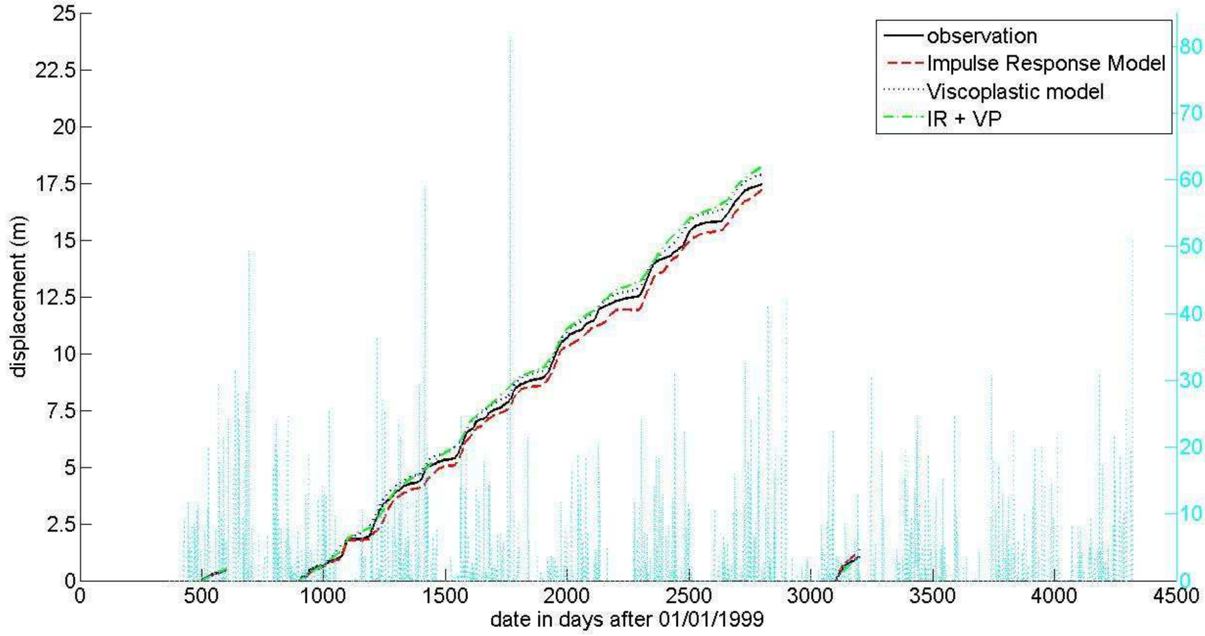

Figure 3 – Cumulated displacements computed from calibrated models and observed

The three models are then applied in a predicted approach: the first step consists in calibrating the models for a 100 days period; the second step is to predict the displacement for 10 more days. The Figure 4 shows the results obtained with such an approach. We can see that the three models overestimate the displacements. The viscoplastic model provides the best predicted displacements, whereas we observe more discrepancies between the cumulative displacements from the combined model (IR + VP) and the observed ones. These results suggest that the mechanical model is more adapted to predict the movements for the 10 following days.

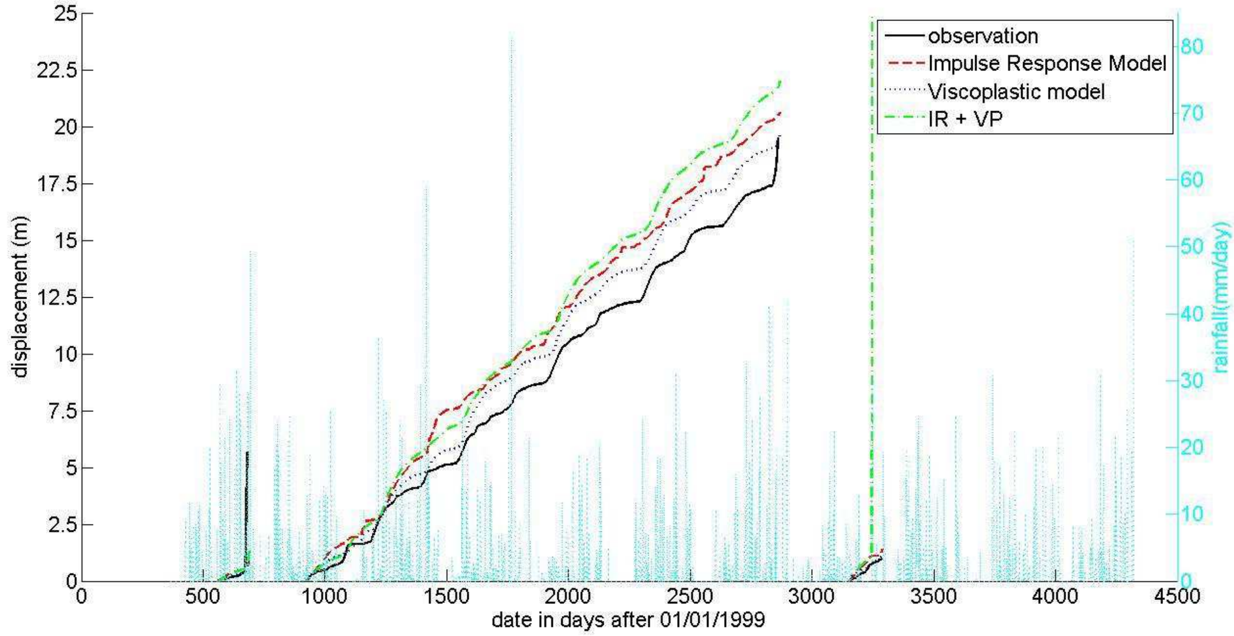

Figure 4 –Predicted and observed cumulated displacements

When looking carefully at the period from 21/08/2006 to 09/11/2006 on Figure 5 before the flow occurs, we can observe that the model is not able to reproduce the displacement with good accuracy prior to the flow. Indeed, the RMSE criterion indicates a large increase, with the value reaching 0.05 m.day^{-1}, 11 days before the flow occurs. This interesting result suggests that the RMSE evolution could be a good indicator of the occurrence of a flow, several days before the flow itself.

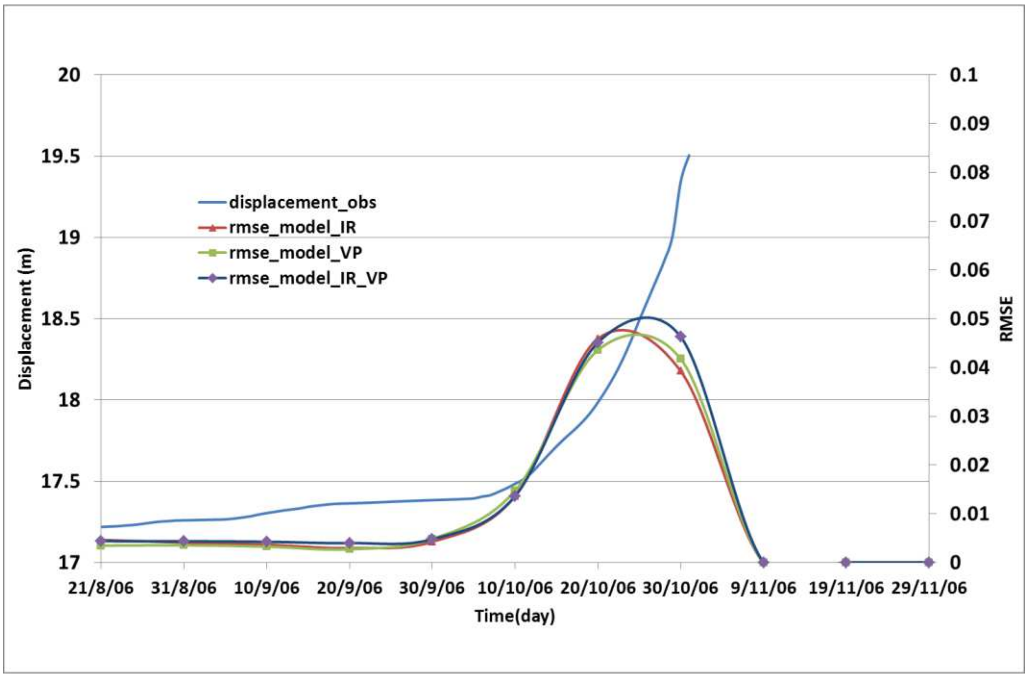

Figure 5 – Observed displacement and RMSE computed before the flow

6 DISCUSSION AND CONCLUSIONS

These results suggest that the impulse response model reproduces the observed data with very good accuracy, whereas the mechanical model seems to be more adapted to predict the movements within 10 days. The RMSE criterion permits to predict the occurrence of the flow as it is demonstrated in Figure 5, with considering all models, 11 days before the flow itself.

However, some improvements could increase the accuracy of the model. Previous tests have demonstrated that the calibration performance depends on the size of the calibrated window. Thus the optimization of the calibration period will be implemented for each calibration. Moreover, it could be interesting to check the sensitivity of the predicted model to the time period of prediction, in particular for shorter period (short term, within a few days) and longer period (long term, for several years).

Finally, when regarding physical aspects, the runoff, which is at the moment not taken into account, is an important phenomenon, which could improve the results.

This study demonstrates the good performances of the 3 models for predicting the movements. They will be used for further studies, in particular with climate change scenario as input.

7 REFERENCES

- Herrera, G., Fernandez-Merodo J.A., Mulas J., Pastor M. Luzi G., Monserrat O. 2009. A landslide forecasting model using ground based SAR data : The Portalet case study, *Engineering Geology*, 105, 220-230.
- Kustas W.P., Rango A., Uijlenhoet R. (1994). A simple energy budget algorithm for the snowmelt runoff model. *WATER RESOURCES RESEARCH 30, n°5 (May 1994): 1515-1527.*
- Malet J.-P. & Maquaire O. (2003). – Black marl earthflows mobility and long-term seasonal dynamic in southeastern France. *In: Proc.1st Int. Conf. on Fast Slope Movements*, Naples, Italy. – Patron Editore, Bologna, 333-340.
- Malet J.-P., Van Asch TH.W.J., Van Beek L.P.H. & Maquaire O. (2005). – Forecasting the behavior of complex landslides with a 2-5D spatially distributed hydrological model. – *Nat. Haz. and Earth Sys. Sc.*, **5**, 1-15.
- De Montety V., Marc V., Emblanch C., Malet J.-P., Bertrand C., Maquaire O. & Bogaard T.A. (2007). – Identifying origin of groundwater and flow processes in complex landslides affecting black marls: insights from an hydrochemistry survey. – *Earth Surf. Proc. and Landforms* 32 (1), pp. 32-48.
- Pinault, J.-L. & Schomburgk S. 2006. Inverse modeling for characterizing surface water/groundwater exchanges, *Water Resour. Res., 42, W08414,doi:10.1029/2005WR004587.*