Local scale groundwater modelling in a landslide. The case of the Super-Sauze mudslide (Alpes-de-Haute-Provence, France)

T.-H. Debieche, V. Marc, C. Emblanch, A.-L. Cognard-Plancq & E. Garel
Université d'Avignon et des Pays de Vaucluse, UMR 1114 INRA-UAPV, Avignon, France

T.A. Bogaard
Water Resources Section, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, Netherlands

J.-P. Malet
CNRS UMR 7516, School and Observatory of Earth Sciences, University of Strasbourg, Strasbourg, France

ABSTRACT: A large scale artificial rainfall has been carried out in the Supersauze landslide to calibrate infiltration models for different soil structure conditions (apparent fissuration density). Two variable saturated 2D models along flow lines were developed with Hydrus software: one with apparent fissures (from field observations) and the other without apparent fissures. The results of the flow simulations indicated that the large water level changes were well estimated by the model, but the low groundwater changes were over-estimated. This is a consequence of the models calibration chosen to simulate fissure flow dynamics rather than matrix flow dynamics. This also resulted in a large difference between the hydraulic conductivities used in the models (10^{-4} m.s^{-1}) and measured in the field (10^{-6} to 10^{-7} m.s^{-1}). In locations where soil macropore connectivity has been detected (from artificial tracing results), the models performed badly. These results showed the limitations of the traditional groundwater modelling approach in such environment. They showed the need to have a stepwise modeling approach with progressive complexity to fit the system heterogeneity. Assimilation of geotechnics data and information on mudslide movement in the models is also requested to improve the simulation of the flow processes.

1 INTRODUCTION

The Super-Sauze mudslide is a typical complex landslide with important soil heterogeneity, matrix and preferential flows and spatial differences in landslide dynamics.

The quantification of the hydrological behaviour is challenging as well as very relevant because hydrology determines to a large extent the landslide dynamics and forecasting or planning of mitigation need thorough understanding of underlying physics.

The objective of this paper is to identify and model the impacts of preferential flows on groundwater changes in landslides developed in black marls.

To achieve this, we have setup a large scale infiltration and tracing experiment.

In this paper we will discuss the experimental setup and the experimental results. Furthermore, we will discuss preliminary results of the unsaturated-saturated zone modelling of the experiment.

2 EQUIPMENT AND METHODS

2.1 *Experimental setup*

The Super-Sauze mudslide is located in the South-east French Alps (France). The elevation ranges from 1740 to 2105 m above sea level and the area is 17 ha. The geology is mostly Callovian-Oxfordian black marls. Artificial rainfall was applied to a 100 m^2 plot (Fig. 1) where slope averaged 20°.

The instrumentation comprised of 6 sprinklers, 15 standard rain gauges, 12 tensiometers (4 STCP 850 from SDEC-France, 4 UMS T4 and 4 Watermark®) located between 0.2 and 0.7 m deep, 7 soil moisture sensors (7 CS615 and CS616 sensors from Campbell) and 38 piezometers (diameter 0.05 m) for water level measurements 1, 2 and 3 m deep.

The depths of filters were 0.5-1 m, 1-2 m and 2-3 m respectively. Bentonite was added between -0,25 and -0,5 m, -0.5 and -1 m and -1.5 and -2m respectively. The remaining hole around the piezometer was filled by sans and soil.

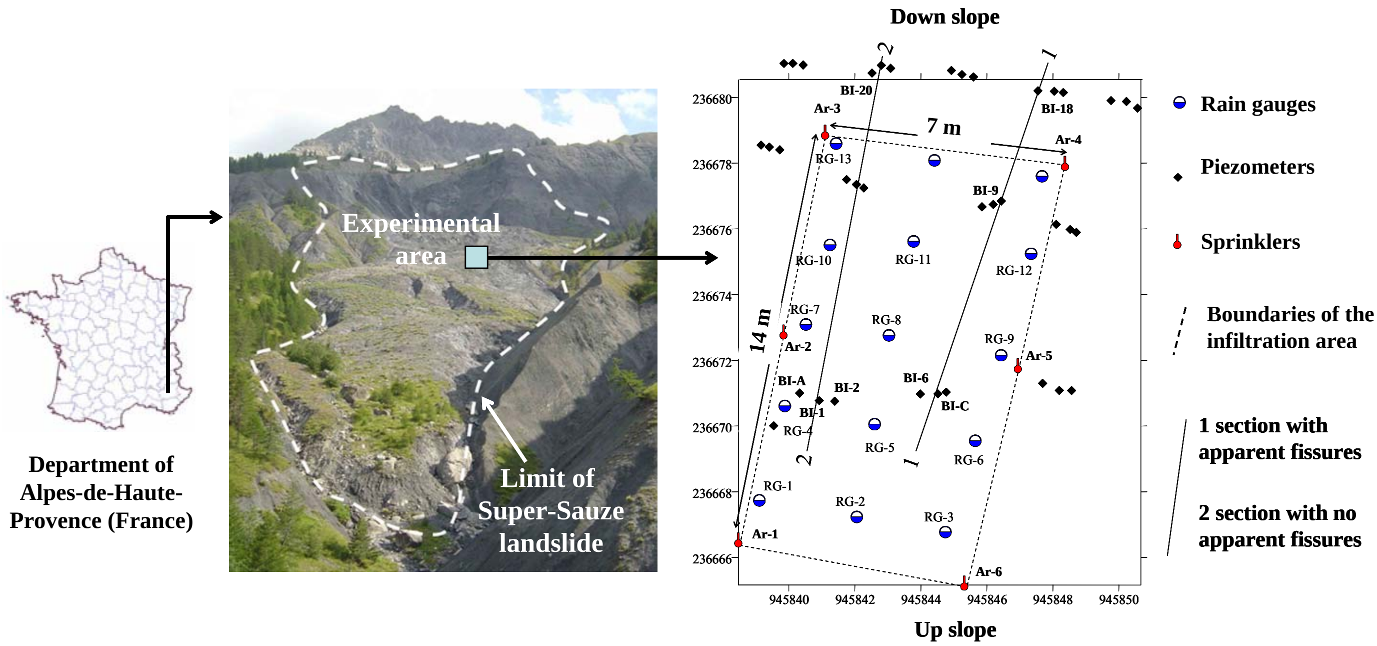

Figure 1. Situation of experiment area.

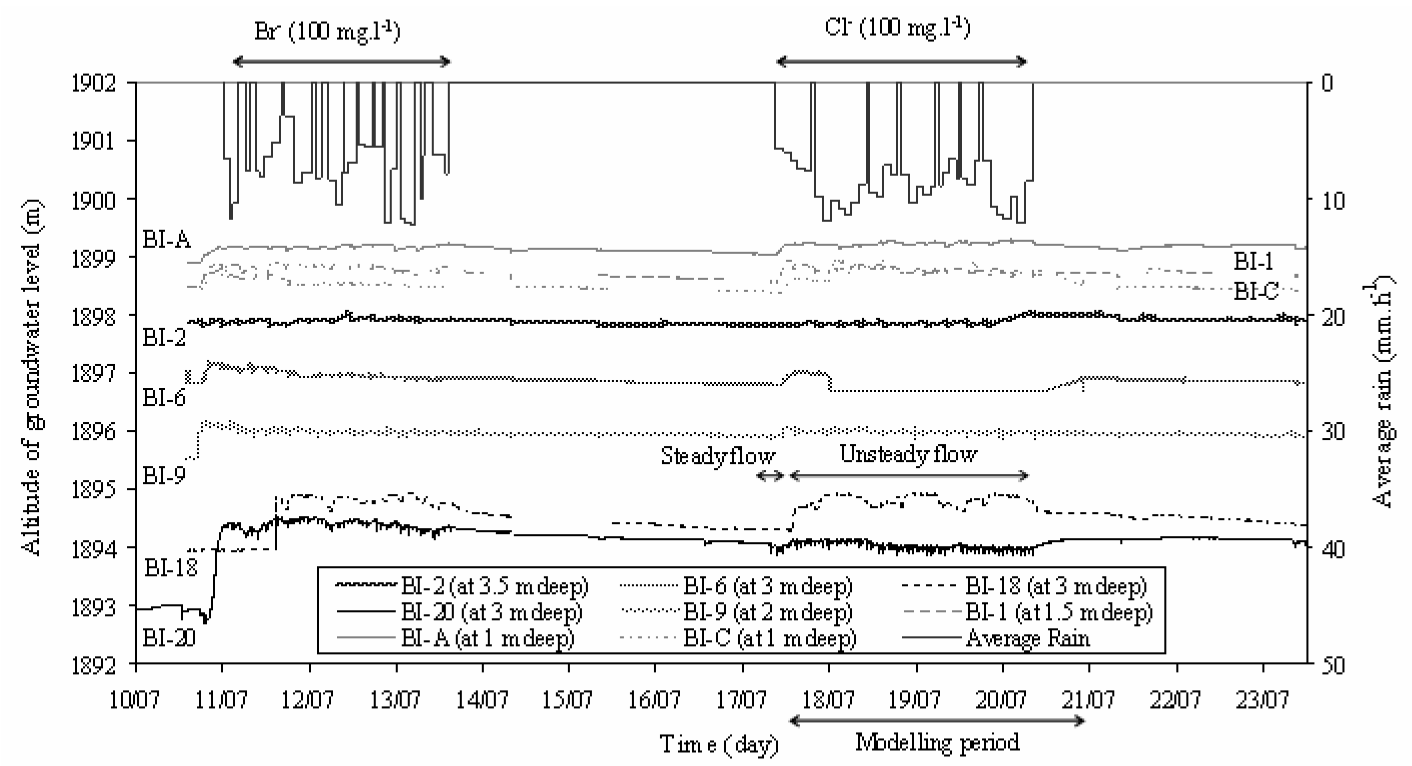

Figure 2. Tracing experiment and groundwater level changes.

Soil moisture, groundwater level and electrical conductivity of water were recorded over the experimental period. The physico-chemical characteristics of water (Temperature, pH, eH and EC) were measured *in-situ* and samples (both surface water and groundwater) were taken for chemical analyses (major elements and bromide).

A total of 1300 samples were collected during the fortnight's experiment with different sampling steps (1, 3 and 6 h). Major anions and bromide were analysed using a Dionex ionic Chromatograph. Cations were measured by Flame Atomic Absorption Spectrometry.

Artificial rainfall was applied over a period of 14 days (10-23/07/2007). KBr was used as tracer during the first week (10-16/07/2007) whereas KCl was used during the second week (17-23/07/2007). The mean rainfall intensity was 8.5 mm.h^{-1} with a mean tracer concentration of 100 mg.l^{-1} (for both Cl^- and Br^-) (Fig. 2).

2.2 Groundwater model setup

The hydrodynamical and hydrochemical monitoring (Debieche et al. 2008) showed 1) different hydrodynamic behaviours (large, medium and low variation of groundwater levels) in the subsurface piezometers; 2) preferential flow in the experimental area, due to the abundant fissures; 3) macropores connection effects due to the water pressure.

Soil hydraulic properties were determined, among others, with slug tests during the experiment and showed that hydraulic conductivity ranged between 10^{-6} and 10^{-7} m.s^{-1}. The geophysical prospecting (Travelletti et al. 2008) with electrical resistivity tomography (SYSCAL Jr Switch-48 device) and seismic reflection techniques indicated that the substratum was approximately at 7 m depth.

In this study, the main modelling objective was to better understand the flow variations in a highly heterogeneous mudslide material. The model strategy was to start with a simple, 2D, homogeneous matrix flow model. Subsequently, more complexity will be added to include the local heterogeneity and preferential flow. By selecting the stepwise increase complexity approach it is possible to identify the effects of increased model complexity on the calculated hydrodynamics. The well-tried Hydrus 2D software was selected (Simunek et al. 1999).

Two modelling sections were chosen parallel to the flow direction: one in the left side (West) of the plot (apparent fissured part, characterized by several fissures at different length (until 2 m) and deep (10 at 25 cm)) and the other in the right side (East, no apparent fissured part). The features of these sections are 1) there was no lateral flow (from West and East) and 2) there were several piezometers equipped with automatic recorders of water head. The period simulated by the model was the second week of the experiment, because the first week had less reliable rainfall data.

As stated above, a first assumption is that the soil structure is considered homogeneous. The soil water retention parameters were measured on 4 samples (2 samples of crumbly marl and 2 samples of cohesive marl) at the INRA Soil Science Laboratory (INRA-Avignon). The results were used in the van Genuchten equations (1980) to estimate the unsaturated hydraulic conductivity.

The boundary conditions of the section consisted upslope of a constant groundwater flux. The lower boundary at the contact limit with the substratum was set to a no flow boundary condition and an atmospheric boundary condition consisting of rainfall and evaporation and with surface runoff at the soil surface was chosen at the surface. The section limits were situated at 50 m upslope and downslope from the experimental area, so that the boundary conditions had negligible impact on the groundwater flow.

The water sampling in the piezometers is included in the model by nodal discharge.

The model was run in two temporal modes:

* in steady flow to simulate the initial conditions of the model before the rain experiment. Therefore a timespan of 1000 days was chosen;

* in transient flow, to simulate the hydrodynamic evolution during the rain experiment.

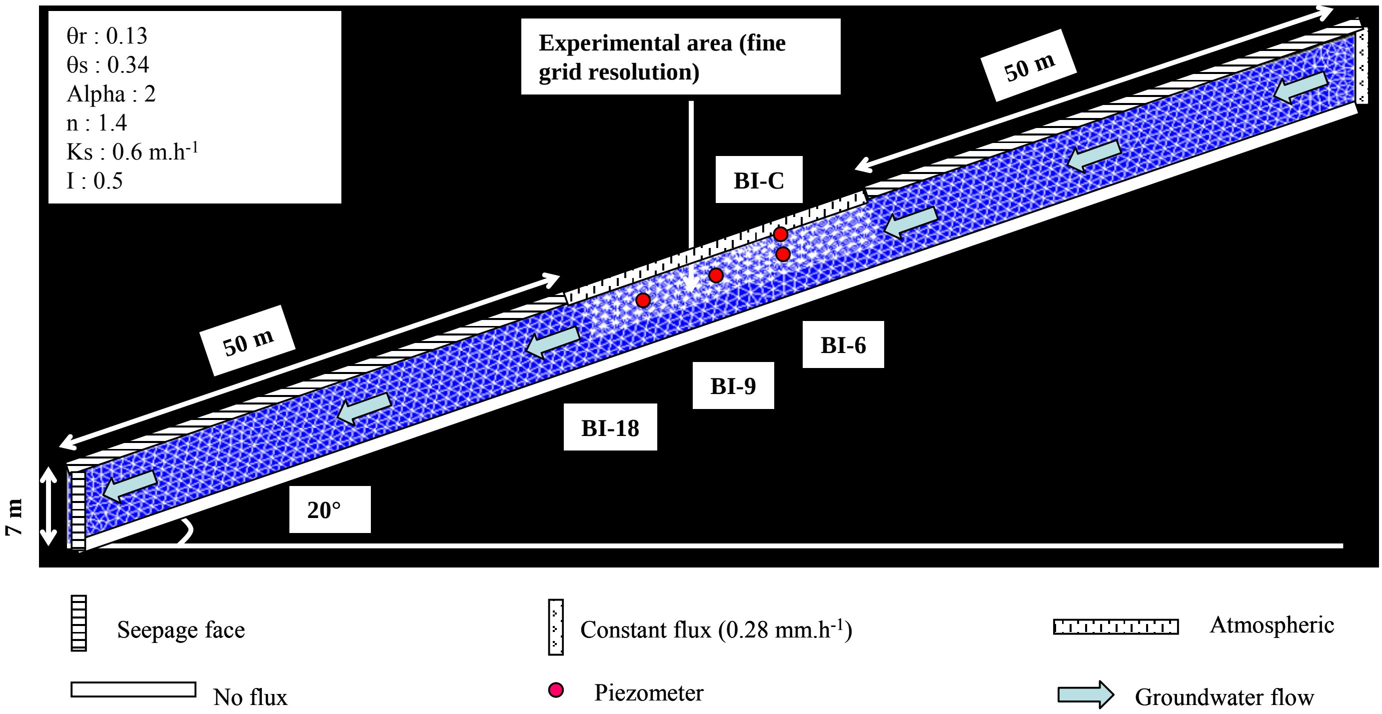

Figure 3. Characteristics and boundary conditions of the model, where: θr is the residual soil water content; θs is the saturated soil water content; alpha is the parameter in the soil water retention function [L^{-1}]; n is the parameter in the soil water retention function; Ks is the saturated hydraulic conductivity [LT^{-1}].

The calibration of hydrodynamic parameters was carried out manually by the trial - error method. The values of hydrodynamic parameters have been optimised to minimise the difference between the measured and simulated groundwater levels. The values obtained for the hydrodynamic parameters are presented in figure 3.

3 DISCUSSION ON THE RESULTS OF THE 2D UNSATURATED-SATURATED ZONE MODEL

The results obtained by the model show several hydrodynamic responses:

- for the piezometers characterised by large water level variation and “normal” sampling (3 or 6 hours sampling time step), the model simulated fairly well the groundwater level (Fig. 4, piezometers BI-C, BI-1 and BI-18). The small difference between measured and simulated values can mainly be attributed to the error in the initial conditions; The model was unable to simulate the water table variation in piezometer BI-C. This result is thought to be related to macropore connection. (soil structure variation over the time of the experiment).

- for the piezometers characterised by large water level variations and with intensive sampling (1 hours sampling time step) the model fitted well with the observation over the starting and recession periods but not during the sampling period (Fig. 5, BI-20). Most probably this error is due to the uncertainty in sampling discharge. The impact of sampling was not correctly simulated because the nodal discharge was kept constant for all the period whereas water sampling resulted in an intermittent process of water extraction.

- for the piezometers with low variations and “normal sampling”, the model performed poorly (Fig. 6, BI-2 and BI-9). This could be due to the calibration criteria, which was focussed on optimising high dynamic groundwater behaviour and not matrix flow.

The comparison between the conductivity measured (10^{-6} at 10^{-7} $m.s^{-1}$) and the conductivity used in the model ($1.7*10^{-4}$ $m.s^{-1}$) showed a very large difference. This is due to the choice to calibrate the model on fissure flow dynamics rather than on the matrix flow dynamics. The field obtained saturated permeability values are not representative for the preferential flow paths as those cannot be determined using standard slug test techniques (they drain or recover too fast). It is clear that the extremely high saturated permeability coming from calibration compensates for the simplified homogeneous, matrix flow subsurface schematisation.

For a correct simulation of groundwater in the piezometers (for large and low groundwater level variations), it is necessary to add the heterogeneity in the lithology of the model and calibrate its hydrodynamic parameters.

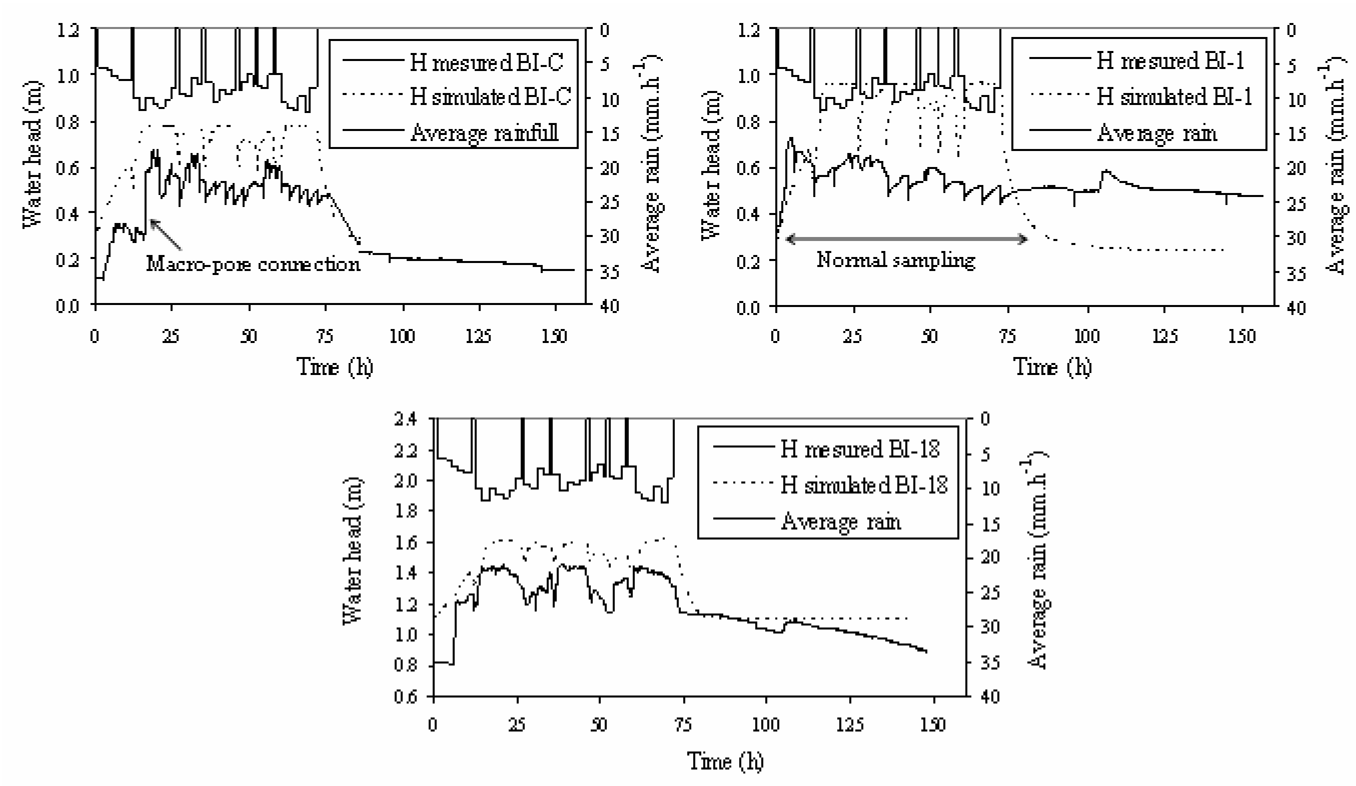

Figure 4. Measured and simulated hydrology for the piezometers characterised by large water head changes and normal sampling in the apparent fissure part (BI-C and BI-18) and no apparent fissure part (BI-1).

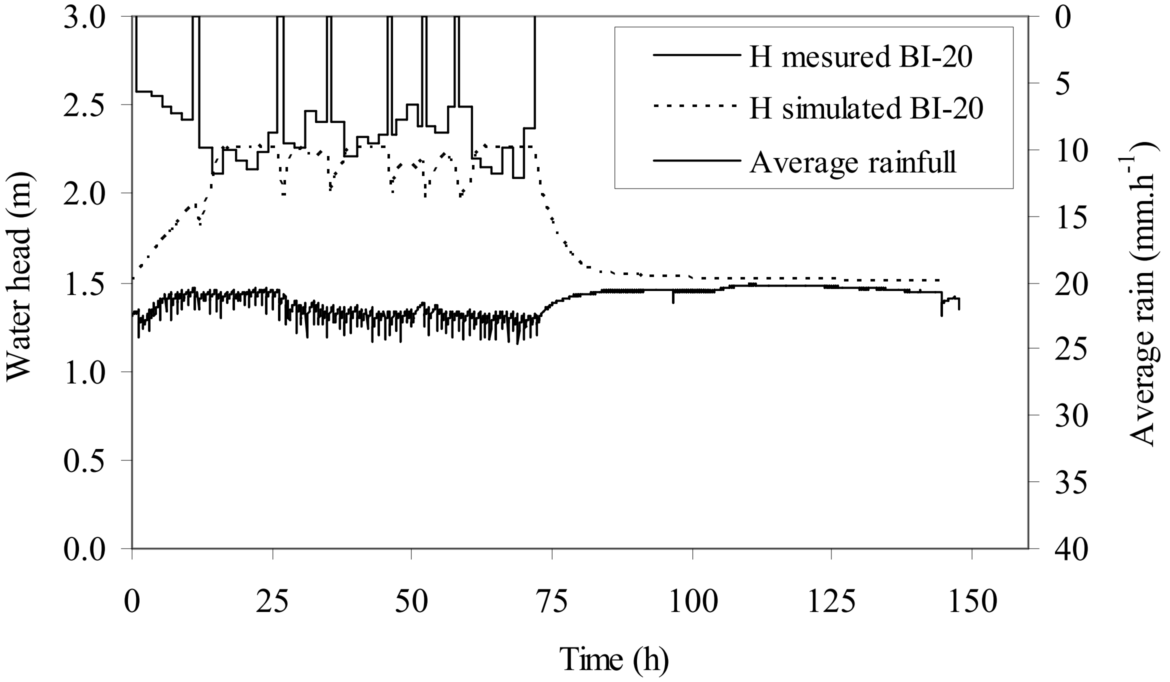

Figure 5. Measured and simulated hydrology for the piezometers characterised by large hydrodynamic changes and intense sampling in no apparent fissure part (BI-20).

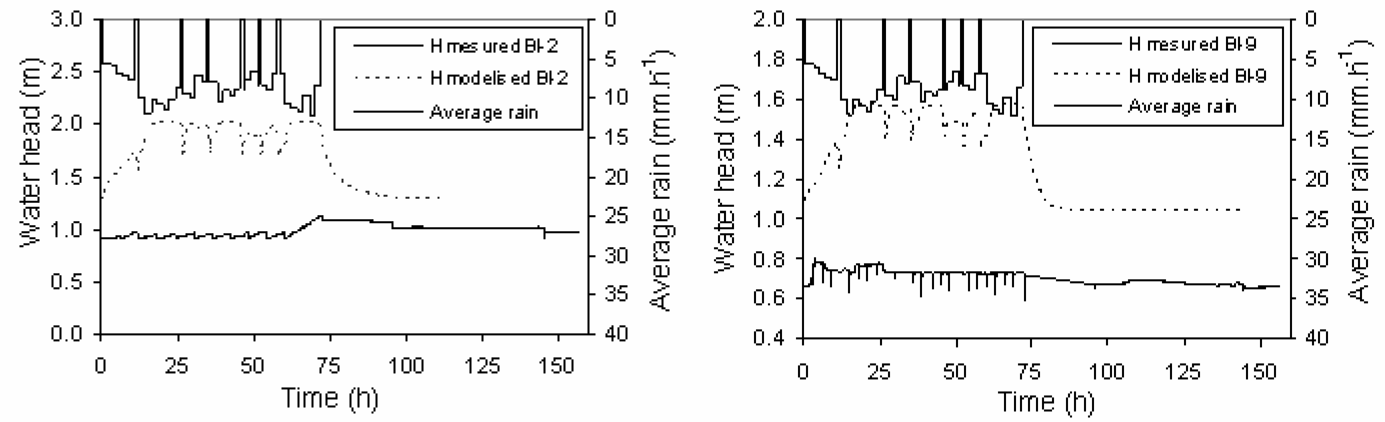

Figure 6. Measured and simulated hydrology for the piezometers characterised by low hydrodynamic changes and normal sampling in the apparent fissure part (BI-9) and no apparent fissure part (BI-2).

4 CONCLUSION AND PERSPECTIVES

The hydrodynamic data and simulation results provided a first quantitative analysis of the relative contribution of matrix and preferential flow in the Supersauze landslide. The model approach with homogeneous lithology, cannot simulate all the hydrodynamic behaviour but was able to simulate some of the larger dynamic variations within the infiltration area. This, however, is at the cost of unrealistic hydraulic permeability and neglecting the regions with matrix like hydrodynamic behaviour, which was poorly simulated. These results are the consequence of the permeability calibration. The model was calibrated on the high dynamic groundwater responses and not on the low frequent dynamics. This is a choice often made in groundwater dynamic modelling in landslide research.

The future work will continue the stepwise modelling approach in which we will add complexity to the model (both lithology and dual flow domains) in order to come to better representation of heterogeneity in pore pressure dynamics.

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