

Tilt and strain deformation induced by hydrologically active natural fractures: application to the tiltmeters installed in Sainte-Croix-aux-Mines observatory (France)

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SUMMARY

We investigate the deformation induced by water pressure variations in hydrologically active natural fractures, and recorded by tiltmeters and strainmeters. The deformation associated with a single fracture is derived using finite-element modelling (FEM). A range in fracture geometries is explored, first to highlight the sensitivity of each geometrical parameter to the deformation, and secondly to allow transfer to observation sites. Water level variations in the fracture are then derived from a hydrological model, driven by observed rainfall, and calibrated on fracture water flow measurements. The modelling results are explicitly applied to constrain the local hydrological contribution to observations with the 100-m-long hydrostatic tiltmeter installed at Sainte-Croix-aux-Mines (France). Our study shows that well-founded physical modelling of local hydrological effect allows a substantial correction of records in observatories.

Key words: Transient deformation; Hydrogeophysics; Hydrology; Continental neotectonics; Fracture and faults; Mechanics, theory, and modelling.

1 INTRODUCTION

Strainmeters and tiltmeters are instruments of special interest for various applications (e.g. see Zürn 1994): measuring earth tides, monitoring active volcanic areas, looking for pre-, co- and post-seismic crustal deformations, checking for mine stability. One important feature is that they are also sensitive to environmental influences, especially hydrological influences that may have amplitudes 10 times larger than atmospheric effects (Edge *et al.* 1981). Some authors (e.g. Dal Moro & Zadro 1998) concluded that hydrological effects should be removed from the recorded deformation signals for the above geodynamic applications (see Zadro & Braitenberg 1999, for a review on this issue). Several methods have been developed in order to model hydrological influences, using linear or non-linear models adjusted on deformation data (e.g. Wolfe *et al.* 1981; Yamauchi 1987; Latynina *et al.* 1993; Westerhaus & Welle 2002). Given the two-fold nature of poroelastic strain (instantaneous and time-delayed contributions) and the potential deformation induced by other hydrological units, any empirical fitting could lead

to inaccurate estimation of corrections for gravity variations (Tervo *et al.* 2006; Longuevergne *et al.* 2009).

Deterministic approaches consider physical modelling of the hydrological contribution considering either individual fractures (Sun 1969; Evans & Wyatt 1984) or treating the subsurface as a homogeneous porous medium (Kümpel *et al.* 1999; Wang & Kümpel 1999). Such modelling allows to use deformation measurements as a tool to monitor variations in water stored in hydrological units (Rerolle *et al.* 2006; Longuevergne *et al.* 2007), and provides complementary information on hydrological processes (Fabian & Kümpel 2003). Tiltmeters have also been used during active hydro-fracturing in order to estimate the extension of the fractured media (e.g. Jahr *et al.* 2006).

In this paper, we focus on deformation induced by changing fluid pressure in fractures, since observatory instruments are rarely installed in porous media. Moreover, it has been concluded from the directional dependence of hydrologically induced deformation that fractures play a dominant role for the hydrological contributions (Edge *et al.* 1981; Peters & Beaumont 1981; Wolfe *et al.* 1981; Yamauchi 1987). Weise *et al.* (1999) identified hydrological effects induced by an aquifer above the instrument installed in granite. While poroelasticity explained the amplitude of the deformation, the orientation, however, was keeping orthogonal to a system of clefts.

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The present study has two complementary objectives.

(1) To physically model the deformation induced by water pressure variations in hydraulically active fractures. A finite element code allows to study a range in fracture geometries. The modelling results are explicitly applied to constrain the local hydrological contribution to observations with a tiltmeter installed at Sainte-Croix-aux-Mines observatory (France).

(2) To assess the potential of tiltmeters and strainmeters as tools to study fracture characteristics and water flow in naturally fractured media.

To reach these goals, a mechanical fracture model and a hydrological model for Sainte-Croix-aux-Mines are derived separately before coupling both using water height variations in the fracture as the link between both models.

2 SITE DESCRIPTION

2.1 Geological context

The mines at Sainte-Croix-aux-Mines (located in the Vosges Mountains, Eastern France, 48.27°N, 7.24°E) form the eastern part of the most important mining works of the Vosgian massif. A kilometer-length hydrothermal vein constitutes the target of the mining in the pre-Cambrian gneiss (Fluck 1996). It has been exploited both at the surface and on the depth since the XVIIth century (Fluck 1996). WilhelmStollen mine, where the tiltmeters have been installed, was dug in the early 1900s in order to reach the lead vein. The cross-cut is straight and encounters orthogonally the vein 500 m after the entrance, just a few meters above the XVIIth-century galleries (see Fig. 1). The superposition of galleries at different depths, and the surface position of the Pingens, indicate a mean dip of N70°E of the eastern part of the vein. However, the electrical tomography

profile (see Fig. 3) shows that the western part of the fracture dips vertically.

2.2 Installed tiltmeters

We set up two orthogonal 100-m base hydrostatic tiltmeters, recently developed by Boudin (2004); Bernard *et al.* (2004). The resolution and long term stability of these instruments are estimated to be better than 10^{-10} and 10^{-8} rad yr⁻¹, respectively (see Boudin *et al.* 2008, for a complete description of the tiltmeter). The instruments were installed in two orthogonal branches of the WilhelmStollen mine. The 160-m-high rock cover ensures a stable environment. Temperature variations are around 10^{-1} °C over the year. The N37°E instrument is set up orthogonally to the exploited vein and the N120°E instrument is along the vein (see Fig. 1). The silica vessels are directly lying on surfaced gneissic rock without any intermediary in order to improve the coupling between rock and instrument.

During the first 2.5 yr of recording (Fig. 2), several lightning and associated electrical problems occurred causing gaps in the time-series, especially on the instrument located along the vein.

A 10-min sampling meteorological station measures rainfall, as well as air temperature, relative humidity, incident solar radiation and wind speed 50 m southwest from the WilhelmStollen mine entrance. From these data, potential evapotranspiration is computed using the Penman–Montheith formulation (Penman 1948; Montheith 1965). Water flow out of the mine is measured daily at the outlet of WilhelmStollen mine and is representative for the integrative amount of water dropping from the fracture ceiling.

2.3 Hydrological context

Rainfall supplies the water in the subsurface fractures. Water precipitation is distributed by a soil layer on top of the hill between



Figure 1. Above-view of site superposed on IGN (French National Geographic Institute) map. Black lines indicate mining galleries, their entrance is indicated with arrow signs in circles (WilhelmStollen, Musloch, Saint Jean and Stimbach). Pingens stands for former surface exploitation of the vein, Heap for surface indications of unknown mining works. Long base tiltmeters are symbolized with blue lines. The red line is the electrical profile. Water flow measurements are performed at the entrance of the WilhelmStollen mine. The meteorological station is situated 50 m southwest from this entrance.

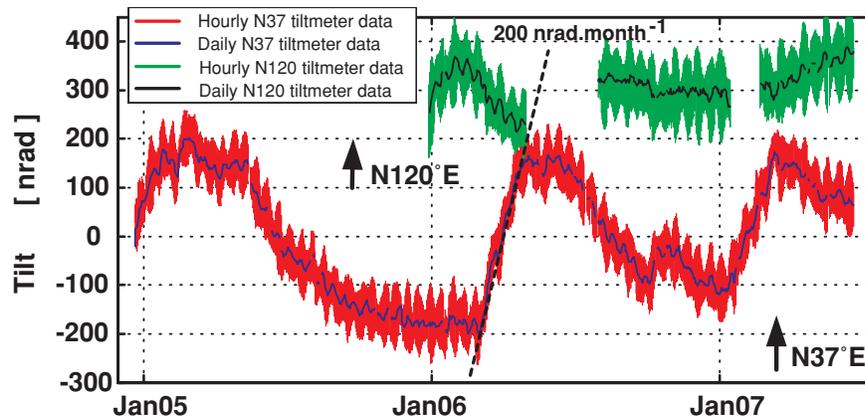


Figure 2. Two and a half years raw data. Red and blue represent decimated hourly and daily data from the N37°E instrument, orthogonal to the vein. Green and black curves represent decimated hourly and daily data from the N120°E instrument, inside the vein.

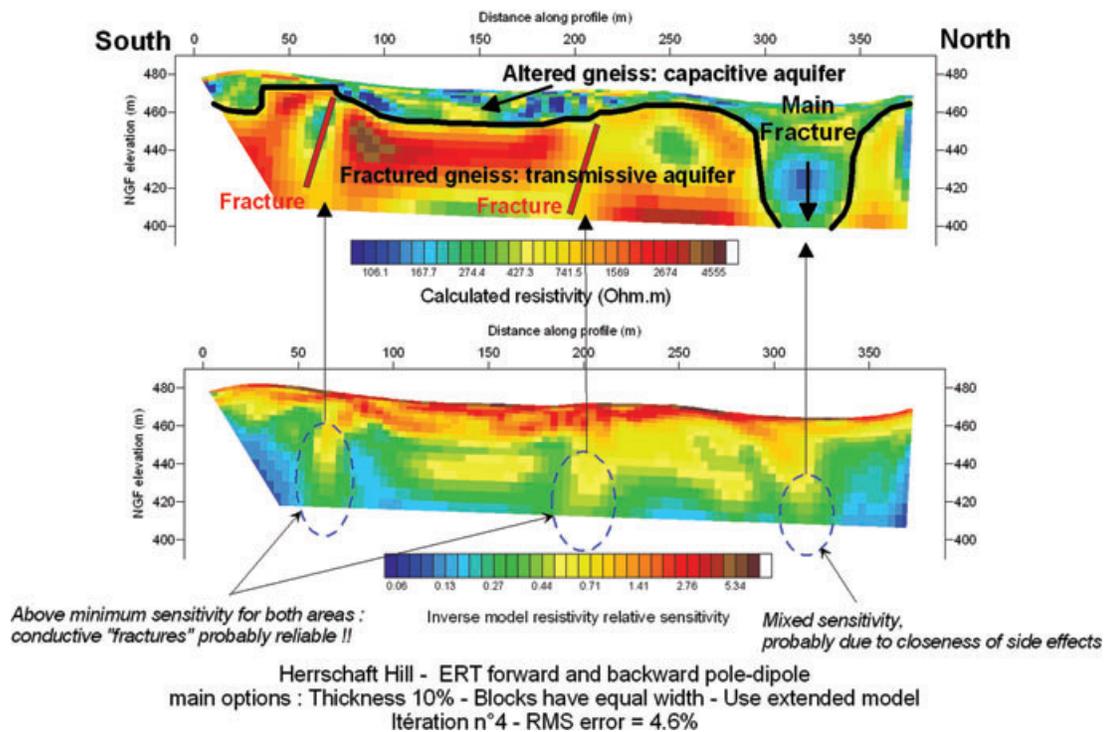


Figure 3. Calculated electrical resistivity of a 384 m long pole-dipole profile and associated relative sensitivity. The geological and hydrological interpretation are superimposed.

surface runoff, evapotranspiration and subsurface infiltration. Both surface and former underground exploitation are preferential pathways for surface water to infiltrate down to the fracture. There is no major infiltration in the crosscut.

An electrical resistivity profile (see Fig. 3) revealed that the top 10–20 m deep first layer is arena (i.e. nearly sand) covering a fractured medium. Under the assumption that the base of the arena is saturated, a lower bound of 20 per cent is estimated for its porosity using Archie's law (Archie 1942). As a consequence, this layer behaves as a capacitive layer and may store a full water layer of a 200 mm full layer of water per metre of soil. Soil layers play the role of a low-pass filter with regard to water infiltration (see e.g. Calder *et al.* 1983; Wu *et al.* 2002; Oudin *et al.* 2004). Consequently, we assume a relatively long-term contribution from this local hydrological unit.

Below the capacitive aquifer lies the fractured layer (or transmissive aquifer). Wyns *et al.* (2004) consider metamorphic rocks unweathered about 60 m below the surface. Below this depth, only main tectonic fractures remain. The electrical profile shows a 20-m-wide altered media above the main fracture. It constitutes the main infiltration pathway to the fracture.

2.4 Temporal signature of fracture deformation

The strong positive correlation between water flow out of the mine and tilt measurements (Fig. 4) suggests that nearby conductive fractures are responsible for the major part of the 400 nrad recorded deformation. Indeed, the main conductive fracture is situated 13.7 m from the northern vessel (Fig. 1).

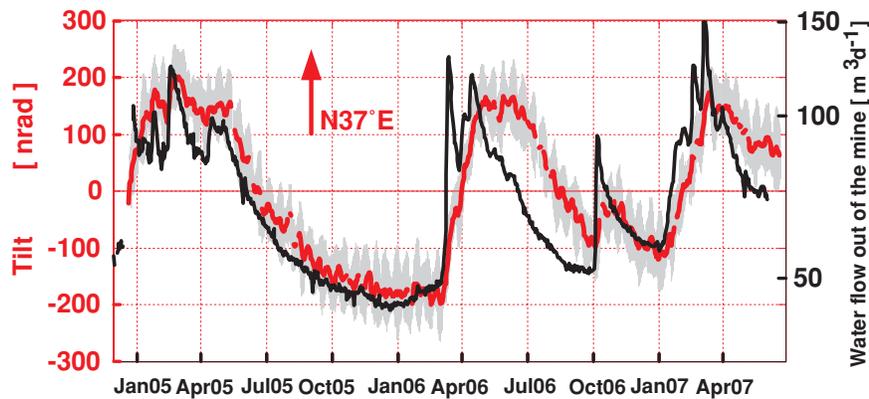


Figure 4. Superposition between N37°E instrument data in red and grey with water flow out of the mine in black on the logarithmic scale on the right.

Fractures may drain a large area and gather a substantial amount of water in a limited thickness unit. As a consequence, an influx of water at the surface could induce a quick variation in water height, and thus a quick variation in pressure. The fracture filling signature is the 200 nrad month⁻¹ apparent drift during 2 months on the N37°E instrument, orthogonal to the fracture, and the very minor effect on the N120°E instrument, quasi-parallel to the fracture. The fracture discharge occurs at longer timescales and induces a slow exponential-like decrease towards equilibrium. While recharge is controlled by the hydraulic properties above the fracture, discharge is controlled by the hydraulic properties next to and below the fracture.

Only connected water induces pressure variations in fractures, and water has to infiltrate down to the top of the saturated part of the fracture, the base level, before generating a deformation. This base level is likely to correspond to the regional hydrostatic equilibrium level, that is, the level of the river in the valley and its associated aquifer (−25 m with respect to the tiltmeter, that is, −185 m with respect to the summit of the hill).

3 DEFORMATION INDUCED BY PRESSURE VARIATIONS IN HYDRAULICALLY ACTIVE FRACTURES

3.1 General considerations

The water level variations in a fracture with time cause a time-dependent modulation of the deformation associated with the regional stress field (see Fig. 5). From a static point of view, a connected water column of height H above a considered position is associated with an increase in normal stress on the fracture planes of $\sigma(H) = \rho_w g H$. Here, H , ρ_w , g denote, respectively, water height above a considered position, density of water and mean gravity value. Thus, a variation ΔH of the height of the water column induces a supplementary stress $\Delta\sigma = \rho_w g \Delta H$.

Four geometrical parameters are relevant to model the deformation.

- (1) The water height variation in the fractures.
- (2) The relative position of the fracture with respect to the instrument (distance and dip).
- (3) The root depth of the fracture.
- (4) The base level of water in the fracture.

Strainmeters and tiltmeters will be differently sensitive to these four parameters. Indeed, the equivalent momentum of this additional

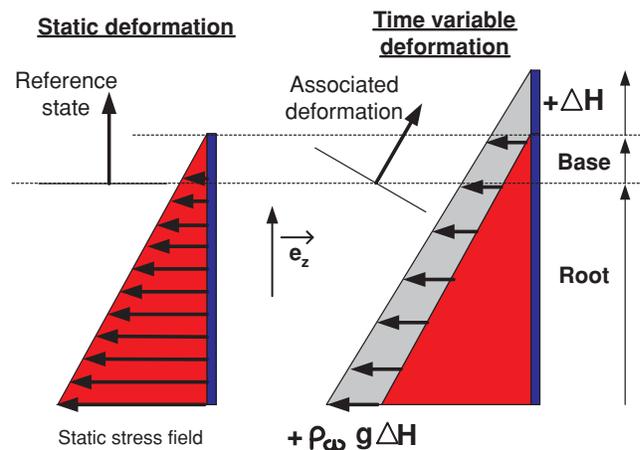


Figure 5. Description of superposed time-variable stress field induced by an additional water height ΔH on a connected water column. Root depth corresponds to the vertical depth of the opened fracture with respect to the instrument and base is the vertical distance between the hydrostatic equilibrium level of water and the instrument. The arrow illustrates the associated deformation of an eventual tiltmeter close to the fracture. The static parameters 'root depth' and 'base' are defined with respect to the instrument. The time-variable parameter ΔH is defined with respect to 'base' level.

pressure field is the most important parameter for tiltmeters, whereas the equivalent force is decisive for strainmeters.

According to the principle of Saint Venant (see Berger & Beaumont 1976), the additional stress field of a heterogeneity modifies the initial stress field over a distance that is equivalent to the heterogeneity characteristic length, that is, in this case the total height of the water column of the fracture. Long base instruments act as spatial filters, so fractures that are too far away, or have a root depth shorter than the base of the instrument, do not contribute to the deformation. Only major hydraulically active fractures have a measurable effect. On the contrary, short-base instruments are more likely to be sensitive to small fractures.

Natural fractures can remain locked open, highly conductive and possess apertures of several millimetres to considerable depth (Dyke 1995). Gentier (1986); Sausse (2002, Fig. 10) showed that the contact area of natural fractures could be smaller than 40–60 per cent for normal stress smaller than 35 MPa (i.e. approximately at a 1500 m depth). For our modelling, we assume that the pressure is applied on the whole area of the fracture, that is, both planes of the entire fracture are separated by a water layer that transmits the

pressure. This water layer may be very thin, as in the example of Pascal's burst barrel. Consequently, the calculated deformation is a maximum effect. Furthermore, we consider only elastic behaviour.

3.2 Mechanical modelling—FEM

No analytical solution referring to the identified deformation process (both applied stress and limit conditions) has been found, so the problem will be treated by means of finite-element modelling (FEM). FEM has previously provided interesting results concerning the investigation of site effects (e.g. Berger & Beaumont 1976; Sato & Harrison 1990), or pressure loading effects (e.g. Kroner *et al.* 2005; Steffen *et al.* 2005). However, the method encounters difficulties in practice, as mentioned by authors, due to difficulties in choosing both relevant boundary conditions and detailed local physical parameters.

FEM was performed with the Comsol Multiphysics software (Comsol, 2006, see www.comsol.com). The modelling of the fracture deformation will be reduced to a single fracture for three reasons.

- (1) On the one hand, the surface deformation field is insensitive to details in the plane of the fracture (Evans 1983).
- (2) On the other hand, we would like to investigate the dependence of the fracture deformation on potential instruments as a function of their relative position to the fracture.
- (3) Our instrument is located at a depth of 160 m, below weathered rock, where only major tectonic fractures remain (Wyns *et al.* 2004).

3.2.1 Model set-up

The problem was reduced to 2-D under the plane strain hypothesis. The domain is a rectangular trapezium with a minimum extent of 30 km, in order to avoid border effects (Fig. 6). The diameter of the triangular mesh is 3 km at the non-loaded boundaries, and the finest resolution is 1 m around the instrumented area. The size of the domain and the associated mesh were determined as the best compromise between stability and accuracy of the deformed domain and the calculation time.

Two more points were defined according to the conditions at Sainte-Croix-aux-Mines. They represent the extension of a 100-m-long instrument (tilt or strain). They are situated 160 m below ground, 13.7 and 113.7 m away from the fracture. When the dip varies, the distance of the instruments to the fracture is kept constant. Tilts and strains are obtained by calculating the difference between

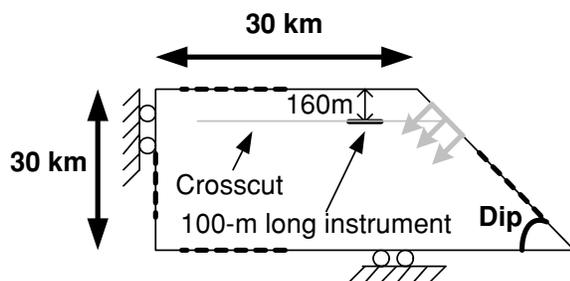


Figure 6. Sketch describing modelled domain and boundary conditions. The arrows correspond to the additional pressure generated by the water height variation as described in Fig. 5.

Table 1. Parameter space explored with finite-element modelling.

Parameter	Minimum value	Maximum value
Root depth	−3000 m	−100 m
Base	−30 m	+10 m
Water height	0.1 m	30 m
Dip	40°	90°

the vertical and the horizontal displacements between these two points and by normalizing this difference to the length.

For simplicity reasons, the 30-km-thick modelled domain is considered as elastic, homogeneous and isotropic gneiss. The elastic parameters were chosen to be those of PREM, that is, a density $\rho = 2600 \text{ kg m}^{-3}$, a Young modulus equal to $E = 68 \times 10^9 \text{ Pa}$ and a Poisson ratio $\nu = 0.28$, which are very close to Gneiss values. Boundary conditions are defined as follows.

- (1) The nodes at the model bottom must not move in a vertical direction.
- (2) The nodes at the vertical model boundaries must not move in a horizontal direction perpendicular to the model sides.
- (3) The pressure induced by the ΔH water height variation in the fracture is applied orthogonally to the fracture, $\rho_w g \Delta H$ on the *root + base* part, and triangular on the ΔH part (see Fig. 5).
- (4) The other boundaries are not constrained.

Two kinds of results were obtained. General results corresponding to a profile of an eventual 1-m-long instrument in the mine crosscut, and a systematic investigation of the parameter space (ΔH , dip, base and root depth) for a 100-m-long instrument located at the site of the tiltmeter. A total number of 10 000 evaluations were carried out, so a mean of 10 values were chosen within a realistic range for each variable, as described in Table 1.

3.2.2 Results

The deformation induced by water height variation $\Delta H = 1 \text{ m}$ in the fracture and recorded by an eventual 1-m-long instrument located inside the crosscut is shown on Fig. 7. Tiltmeters and strainmeters provide complementary information. In the case of tiltmeters, the direction of the induced tilt is generally oriented towards the fracture (positive deformation), but may also be oriented towards the other side. The zero deformation in the crosscut gives information about the dip of the fracture. In the case of strainmeters, the maximum deformation is located at a distance that is equivalent to the total height of the water column. This example shows how deformation instruments may be used as tools to better constraint the characteristics of hydraulically active fractures. Several instruments located along a profile categorize the different fracture geometries quite well.

The deformation induced by water height variation $\Delta H = 1 \text{ m}$ in the fracture on an eventual 100-m-long instrument located at the place of the tiltmeter is shown on Fig. 8. The systematic investigation of the parameter space enable to draw the following conclusions.

- (1) As noted previously, tilt deformation gives little information concerning the relative position of the hydrostatic level in the fracture. Tilt deformation is especially generated by the relative depth of the saturated part of the fracture with respect to the instrument. Note that dip plays an important role as well.
- (2) Conversely the depth of the saturated part of the fracture does not contribute to the amplitude of the strain. As expected, strain deformation is due to the proximity of the water layer,

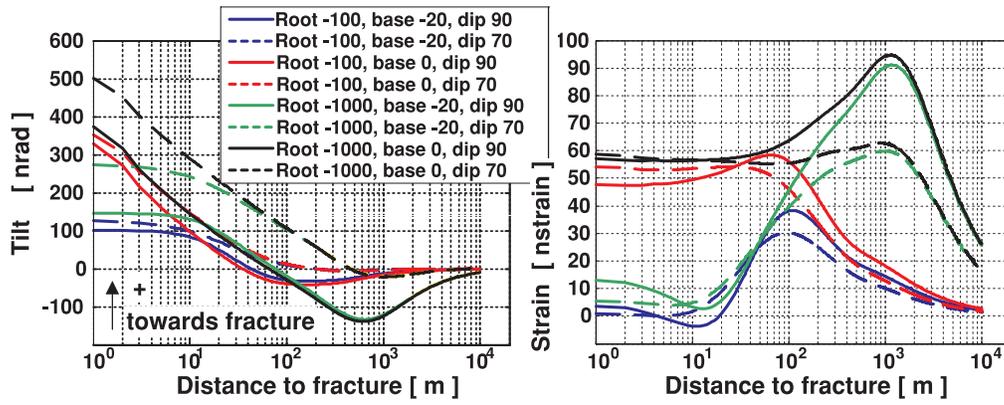


Figure 7. Calculated tilt and strain deformation with $\Delta H = 1$ m, and various fracture geometries for a 1-m-long instrument located on the crosscut.

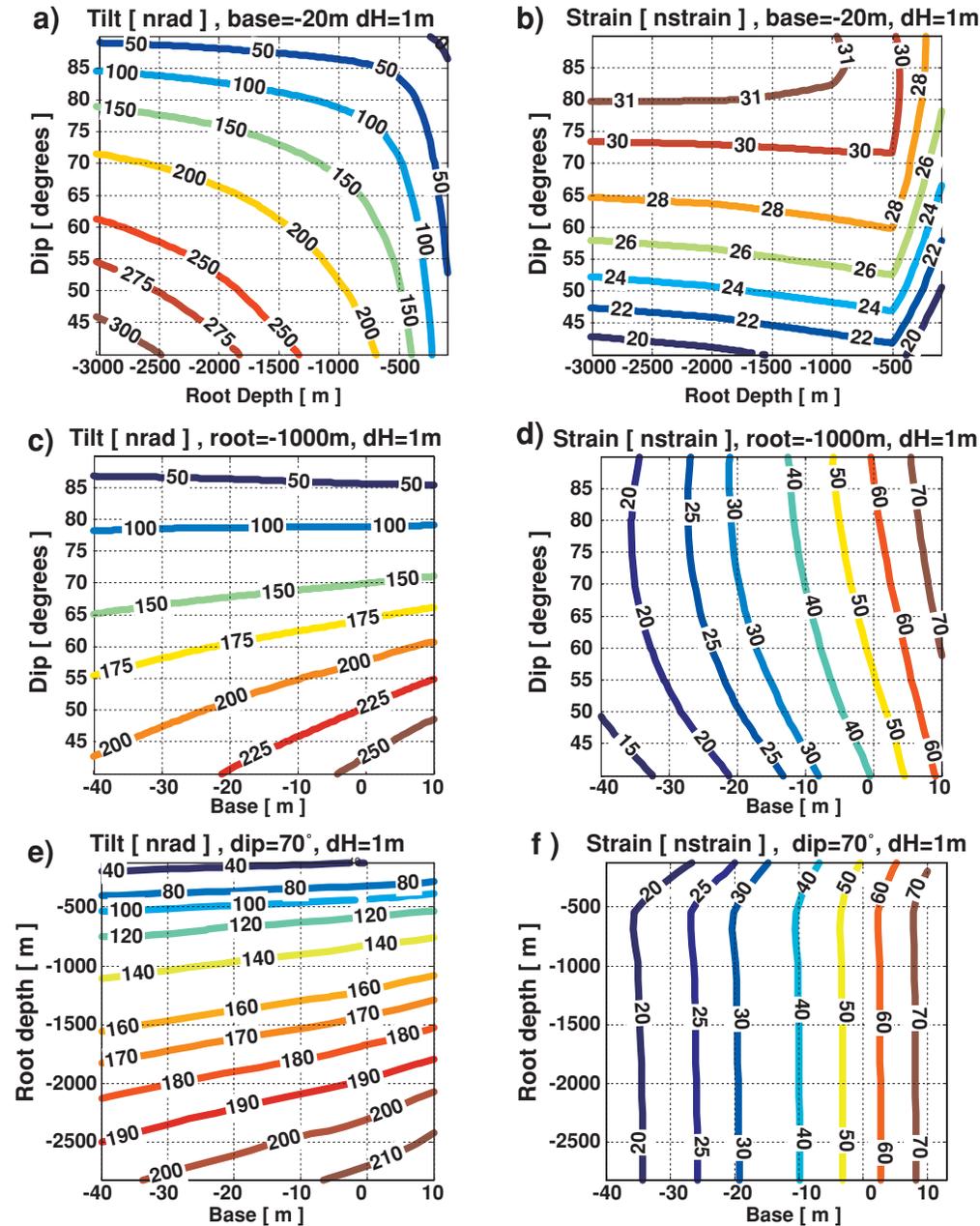


Figure 8. Exploration of parameter space for $\Delta H = 1$ m and a 100-m long instrument. Calculated tilt deformation with $base = -20$ m (a), $root = -1000$ m (c), $dip = 70^\circ$ (e). Calculated strain deformation with $base = -20$ m (b), $root = -1000$ m (d), $dip = 70^\circ$ (f).

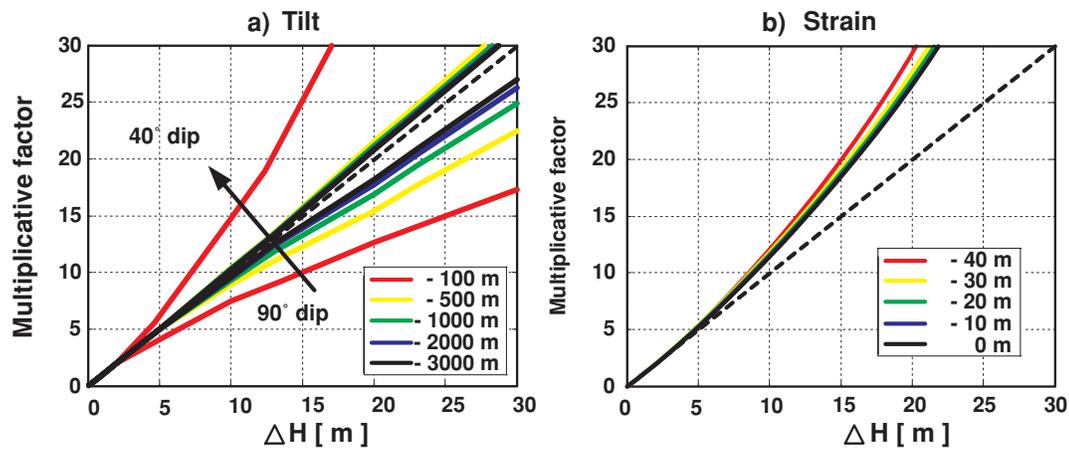


Figure 9. (a) Envelop curves (classified by root depth) illustrating the linearity of tilts towards varying water height variations ΔH for a 100-m long instrument and fixed $base = -20$ m. (b) Mean curve illustrating the linearity of strain deformation of strains towards water height variations ΔH for a 100-m-long instrument and fixed $root\ depth = -1000$ m.

and so increases quickly as the base water level becomes more and more positive. The dip of the fracture has a minor effect on strains.

(3) The induced deformation decreases when the length of the instrument becomes equivalent to the size of the additional pressure field (see Figs 8a and b cases).

(4) Due to numerous equivalences between the different geometries (especially dip/root depth couple for tilts, and base/ ΔH couple for strains, see next section), the determination of the fracture geometry using a single instrument is not possible. On the other hand, it could give realistic minimum and maximum parameter values.

(5) Tiltmeters and strainmeters are complementary instruments, that is, the use of both instruments as tools to investigate hydraulically active fractures could dispel the equivalences.

3.2.3 Linearity of deformation

The previous results were calculated for a 1-m-water height variations in the fracture. The introduction of the ΔH parameter is shown on Fig. 9. The deformation may be considered as linear towards the ΔH parameter as long as $\Delta H \ll rootdepth + base$. In this case, both the application point of the equivalent force and the application point of the equivalent momentum may be considered as unchanged. When ΔH increases, the potential non-linearity mainly depends on the depth of the saturated part of the fracture with respect to the instrument. Note that tilts keep highly sensitive to the dip of the fracture and that strains increase dramatically with ΔH .

3.2.4 Effect of the instrument base-length

Several authors (e.g. D'Oreye de Lantremange & Zürn 2006) consider that the amplitude of local effects is lowered when using long-base instruments. As predicted by Saint Venant's principle, this assumption is verified when the characteristic length of the heterogeneity is smaller than the instrument base-length. However, this assumption may not be verified when the instrument base-length is smaller than the heterogeneity. Fig. 10 shows that, for definite fracture geometries, strains may increase when the instrument base-length is increasing. The amplitude of tilts is also increasing with the base length of the instrument when root depth is positive (not shown).

When the instrument base-length is decreasing, strains and tilts become very sensitive to the geometrical parameters. Thus, any local variation of these parameters may have a substantial impact on the amplitude of the recorded deformation. An accurate modelling of the deformation becomes more difficult.

4 HYDROLOGICAL MODELLING

4.1 Determination of drained area

Hydrologists are used to work on data reduced to unit area. For the fracture, runoff measurements out of the mine Q_{mes} in ($m^3 d^{-1}$) are divided by the area drained by the fracture $S_{drained}$, so that $Q = Q_{mes}/S_{drained}$. In this way, reduced runoff Q is a flux, comparable with rainfall measurements and potential evapotranspiration evaluations, in ($mm d^{-1}$).

Surface geometrical investigations allow to estimate the area drained by the fracture at 30 000 m^2 . This is the most likely value, but it can also be included in the (20 000–60 000) m^2 interval depending on the fractured layer on top of the hill.

This reduced run-off will be used to calibrate the hydrological model. As a consequence, the model calculates 'reduced' hydrological water height variations in the fracture ΔH_{hydro} . The water volume conservation in the fracture then allows to estimate the 'mechanical' water height variation ΔH that will force the FEM model: $S_{drained} \Delta H_{hydro} = \frac{length_{frac} \cdot width_{frac}}{\sin(dip)} \Delta H$, where dip stands for the dip of the saturated part of the fracture, $length_{frac}$ and $width_{frac}$ stand respectively for the fracture length involved in the hydrological unit, and the fracture width. $width_{frac}$ parameter corresponds to the equivalent aperture of the fracture where the water level is varying. Note that for a definite amount of water, thinner fractures could possibly generate greater water height variations in the fractures. However, hydrologically speaking, thinner fractures are probably less conductive as well.

When calculating water height variations, drained area influences both the calculation of the total run-off Q and the calculation of the final 'mechanical' water height variation ΔH . However, as the measured total amount of water $S_{drained} \Delta H_{hydro}$ is fixed and determined, the uncertainty associated with the calculation of the forcing variable ΔH will not depend on the uncertainty on drained area.

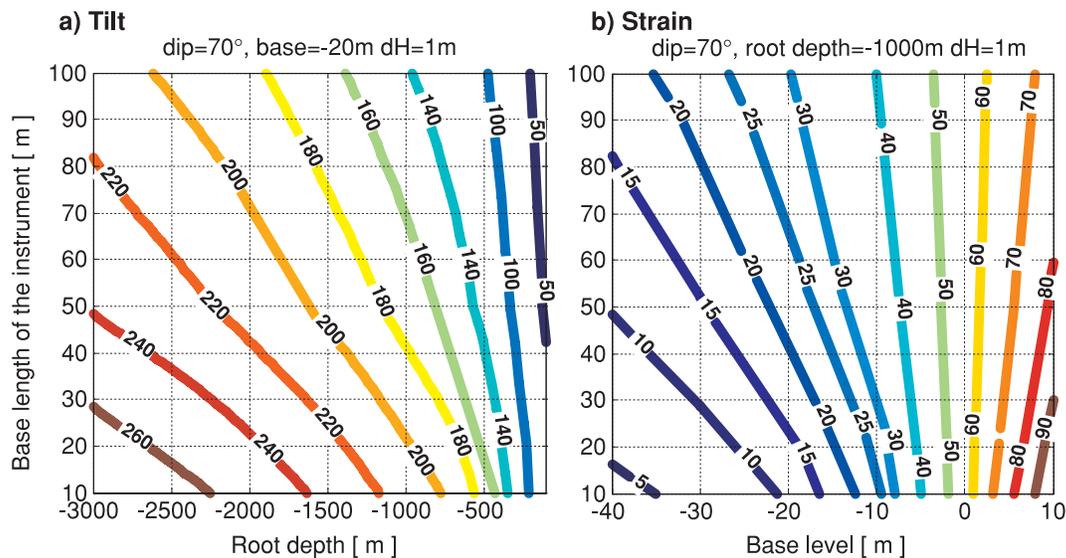


Figure 10. Modelled deformation for $\Delta H = 1$ m and a 70°-dip fracture illustrating the effect of the instrument base-length; a) on tilts with respect to the fracture root depth for a fixed $base = -20$ m; b) on strains with respect to the hydrostatic base level for $root\ depth = -1000$ m.

Table 2. Observed and estimated annual amplitude of hydrological processes for a median drained surface (30 000 m²).

Process	Observed annual value	Estimated annual value
Rainfall P	1220 mm	–
Mine runoff Q	430 mm	–
Deep drainage Q_{deep}	–	280 mm, i.e. 0.63 Q
Potential evapotranspiration PE	680 mm	–
Actual evapotranspiration AET	–	510 mm

4.2 Annual mass balance and deep drainage

A main difficulty when coupling hydrology and geodesy is the need to calculate the amount of stored water, whereas hydrological tools are build up to manage fluxes (rainfall, evapotranspiration and runoff). This implies to model carefully all hydrological processes, and feed hydrological models with a data set as realistic as possible in order to avoid compensations or cumulative errors when calculating the amount of water. Annual mass balance may help to check the realism of fluxes.

The amount of water flowing out of the fracture under study is not limited to the measured quantity Q at the outlet of the mine. Indeed, a supplementary amount of water Q_{deep} is drained by Musloch mine, below WilhelmStollen mine. An estimation of the annual total runoff out of the fracture can be deduced from the Turc–Pike relationship (Turc 1954; Pike 1964) linking annual runoff out of a hydrological unit to annual potential evapotranspiration and annual precipitation. The annual total run-off is estimated to 710 mm, so deeper drainage is calculated as $Q_{deep} = 0.63 Q$.

The annual mass balance $P = AET + Q + Q_{deep}$ also allows to estimate actual evapotranspiration $AET = 510$ mm. Note that nearly half of annual rainfall is used for evapotranspiration. Annual mass balance considerations are summarized in Table 2.

4.3 Hydrological model set up

We chose to use a simple conceptual hydrological model in order to evaluate water height variations in the fracture for several reasons.

(1) From a conceptual point of view, as stated by Zürn *et al.* (2007), simple models give good orders of magnitude, and contain only essential processes that allow to provide insights into hydrological processes, before using more complicated models with more parameters.

(2) From a hydrological point of view, hydrological models are also subject to numerous equivalences between parameter sets when they are calibrated using only water flow data (what is called equifinality, see Beven & Freer 2001). Therefore, several descriptions of internal processes are similarly efficient with respect to runoff simulations. The use of parsimonious models makes it possible to cope with overparametrization.

Conceptual hydrological models are based on a rough simplification of the various physical processes that take place in hydrological systems (e.g. evapotranspiration, generation of water flow, etc.). As a consequence, they are not built to simulate explicitly internal processes. However, they may give substantial information: previous research showed for instance that the moisture rate of the modelled soil layer may be informative to represent the hydric state of a basin (Oudin *et al.* 2006). As each model is built on different assumptions, the choice of the model is decisive concerning its ability to describe an internal process.

Several models were tested in order to estimate infiltration inside the fracture, most of them taken from Chapman & Malone (2002). The concept of the IHACRES conceptual lumped model (Jakeman *et al.* 1990; Littlewood & Jakeman 1994) was chosen because it represents the soil-atmosphere interface for this hydrological system better than the others. This model is available as a free software (Littlewood *et al.* 1997) on the Internet web page of the Centre for Ecology and Hydrology (UK) <http://www.ceh.ac.uk/products/software/CEHSoftware-PC-IHACRES.htm>.

We use a modified version of IHACRES, called IHAC, in order to feed the model with potential evapotranspiration as an input variable instead of temperature data. This modified model is shown on Fig. 11 and has been described and used several times, for example, by Oudin *et al.* (2005). This model is built with three stores modelling soil behaviour (S store, i.e. humidity index), quick behaviour of the hydrological system (T store) and slow behaviour

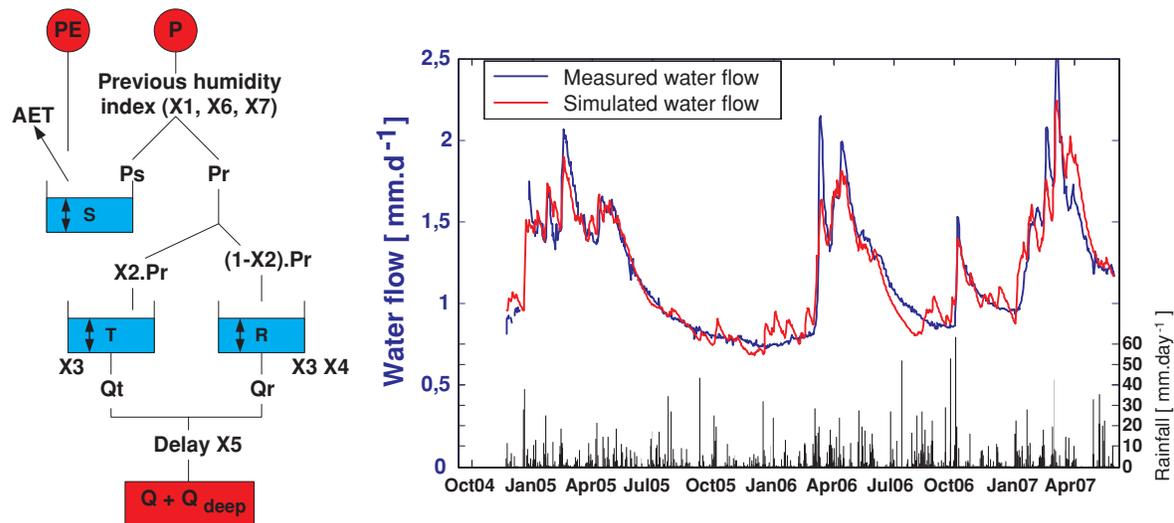


Figure 11. Diagram of the modified IHAC lumped model based on 7 parameters (X1-X7). In red, forcing data, PE , P , Q and Q_{deep} stand for potential evapotranspiration, precipitation, runoff out of the mine and deep run-off, respectively. In blue, S , T , R correspond to modelled water-height in the three stores, respectively soil, quick and slow stores. R store level variations are used to estimate water height variations in the fracture ΔH_{hydro} .

(R store). Seven parameters are associated with these stores: $X1$, $X6$ and $X7$ drive the antecedent-humidity index, $X2$ separate the amount of water between the quick and slow stores, $X3$ and $X4$ are drainage constants for these two stores. The level variations in the slow store (R store) are used to estimate water height variations in the vein ΔH_{hydro} .

At daily time steps, deep drainage is calculated as $Q_{\text{deep}} = 0.63 Q$. The model is fitted on daily total water flow out of the fracture $Q + Q_{\text{deep}}$. The Nash–Sutcliffe efficiency (Nash & Sutcliffe 1970) is 0.89 (1 indicating a perfect description of the water flow out of the mine) with an rms error of 0.1 mm d^{-1} , the total amount of water being respected by less than 0.1 per cent. The model confirms the expected low-pass filtering behaviour of soils towards infiltration: the soil layer can absorb half of the annual precipitation amount, and the calculated time delay between rainfall and runoff generation is 5 d.

The model calculates an annual water height variation $\Delta H_{\text{hydro}} = 200 \text{ mm}$ in the slow store, which corresponds to an equivalent $\Delta H = 8.7 \text{ m}$, considering a 1-m fracture width.

5 COUPLING OF MODELS AND DISCUSSION

5.1 Choice of fracture parameters using annual variation

The first part of our research was devoted to gathering *a priori* information to constrain the parameter values, as shown in Table 3. Considering a mean dip of 70° and a base level of -25 m , several models could explain the 400 nrad annual deformation with

a medium water height variation. For example, a fracture with a root depth of 500 m and a 4 m water height variation within the year is plausible, as well as a 100 m root depth and a water height variation of 16 m . In both the cases, the width of the fracture must be of the order of 1 m to satisfy the hydrological considerations. This is an important result since the observed deformation could be completely explained by water height variations in the Musloch gallery below the instruments.

5.2 Local hydrological contribution to tilt time-series

The time variable reduced water height variation ΔH_{hydro} calculated with the hydrological model is transformed into the ‘mechanical’ water height variations ΔH and into tilt deformation using the fracture geometric parameters determined in the previous section. Fig. 12 shows the comparison between modelled deformation induced by the fracture and the recorded signal corrected from regional scale surface loading (see Longuevergne *et al.* 2007). As stated previously, this local-scale deformation creates especially a long-term contribution to tilt deformation, except at fracture-filling periods.

Recorded tilt deformation is not corrected from deformations induced by atmospheric pressure variations. It typically induces a 30 nrad signal with a 3–10 d period. The residuals also show a 500-d period signal yet unexplained, which could be linked to an erroneous estimation of hydrological fluxes. Longer time-series and further studies on the modelling of the hydrological contribution are needed to improve the understanding of the recorded signals.

Table 3. Table summing-up *a priori* informative elements and main informative tools.

Fracture parameter	<i>A priori</i> elements	Main informative elements
Base level	Geometry, regional hydrostatic level	Strainmeter
Root depth	Lithostatic pressure	Tiltmeter
Annual water height variation	Geometrical considerations	Annual mass balance, tiltmeter and strainmeter
Dip	Geology	Geology and tiltmeter
Atmosphere-soil interface	Pedology	Geophysics and hydrological model
Time varying water height variation	Water flow out of the mine	Hydrological model, tiltmeter and strainmeter

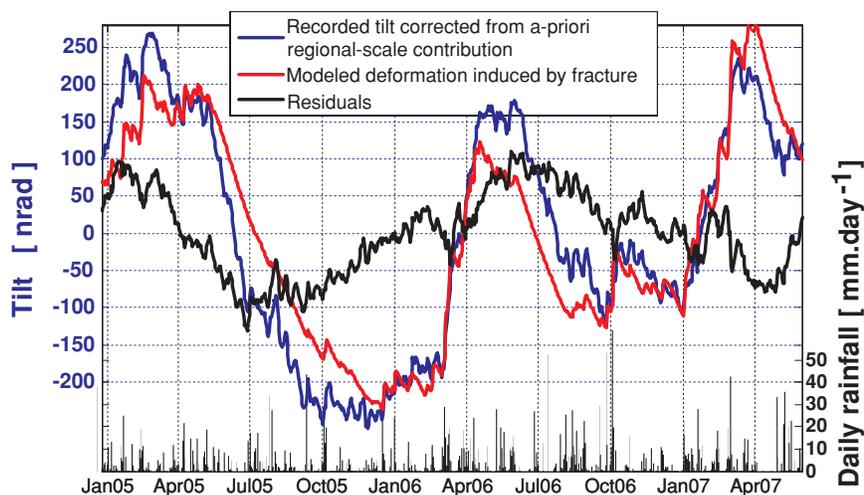


Figure 12. Tilt time-series corrected from local hydrological effect using determined parameters (in blue). In red is shown the modelled deformation induced by the modelled nearby fracture. Note the 3–10 d signal is typically induced by pressure variations.

6 CONCLUSION

In this paper, we addressed the deformation induced by hydrological subsurface processes to strainmeters and tiltmeters at the newly installed observatory in Sainte-Croix-aux-Mines. Physical modelling is applied to study the deformation induced by natural hydraulically active fracture in response to water pressure variations. The mechanical behaviour of large fractures with respect to the identified deformation process is constrained using FEM modelling. A range of geometric parameters is investigated to determine the parameter space and allow transfer to other observation sites. Water pressure boundary conditions are derived from a hydrological model, driven by observed rainfall and evapotranspiration and calibrated on water flow. The coupled mechanical and hydrological modelling show a good agreement with the 100-m base hydrostatic tiltmeters observations. In particular, fracture filling and slow drainage are well described. We show that an accurate estimation of the hydrological contribution cannot be reduced to the knowledge of rainfall alone, especially at annual timescales.

The deterministic approach allows to draw conclusions on two points of interest. On the one hand, our model allows a substantial correction of records in observatories to better study geodynamical signals. On the other hand, better constraints on the characteristics of fractures may be gained from using these sensitive instruments.

Finally, this paper also allows to draw—more precisely confirms—general recommendations about the installation of future instruments in order to lower the amplitude of hydrologically induced fracture deformation (especially in a metamorphic context).

(1) The setting-up of instruments in the weathered layer, at the soil-atmosphere interface, should be avoided. In a metamorphic context the altered layer could be 10–20 m thick, and the fractured layer could be 50 m thick (Wyns *et al.* 2004).

(2) An extremely small percentage of visible fractures may be hydrologically active. If so, it would be interesting to measure runoff in order to monitor an eventual local-scale deformation.

(3) Short base instruments are more likely to be sensitive to eventual short hydraulically active fractures than longer instruments.

(4) Generally speaking, the hydrologically induced contribution cannot be avoided. This assessment implies that the estimation of the hydrological contribution is easier in homogeneous hydrologi-

cal contexts where hydrological monitoring could be representative over large areas.

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