Geodetic tools for hydrogeological surveys: 3D-displacements above a fractured aquifer from GPS time series

Frédérique Moreau, Olivier Dauteuil

To cite this version:

Frédérique Moreau, Olivier Dauteuil. Geodetic tools for hydrogeological surveys: 3D-displacements above a fractured aquifer from GPS time series. Engineering Geology, Elsevier, 2013, 152, pp.1-9. 10.1016/j.enggeo.2012.10.017 . insu-00811758

HAL Id: insu-00811758
https://hal-insu.archives-ouvertes.fr/insu-00811758

Submitted on 12 Apr 2013

Geodetic tools for hydrogeological surveys: 3D-displacements above a fractured aquifer from GPS time series.

Authors: Frédérique Moreau and Olivier Dauteuil

Affiliation of authors: University Rennes 1, Geosciences Rennes, CNRS UMR 6118,

Address : 263, Avenue du Gal Leclerc, CS74205, 35042 RENNES Cedex, France
e-mail : frederique.moreau@univ-rennes1.fr
olivier.dauteuil@univ-rennes1.fr

Corresponding author:
Frédérique Moreau
e-mail : frederique.moreau@univ-rennes1.fr
tel : (33) 2 23 23 61 07
fax : (33)2 23 23 61 00
address : University Rennes 1, Geosciences Rennes, 263, Avenue du Gal Leclerc, CS74205, 35042 RENNES Cedex, France

Abstract

Deep porous reservoirs are subject to charge and discharge of fluids (oil, gas or water), either naturally or induced by human exploitation. This leads to a variation in pressure inside the reservoir and consequently to a deformation of the overlying material. The knowledge of the ground surface displacements allows inferring the fluid migrations and the hydromechanical properties in the porous reservoir. Different kinds of geodetic tools are able to measure this ground deformation: GPS, radar interferometry InSAR, tiltmeters or leveling. Each of them has its own spatial and time characteristics and accuracies that conduct to different kind of applications. After a review of the geodetic studies applied to hydrogeological processes, we describe two examples of GPS time series measurements above the granitic fractured aquifer of Ploemeur, located in French Brittany. These time series records the 3D-displacements induced by the sum of different processes. In this site, the involved processes are mainly the ground deformation related to piezometric level variations in the aquifer that we are looking for and the ocean tide loading that can reach several centimeters in the study area. We present the protocol of the GPS data survey and the processing strategy applied to extract the effect of hydrogeological process with sufficient accuracy. Two different experiments were studied: the long term deformation corresponding to seasonal hydrological cycle and the short term deformation associated to a pumping test. For a same variation in piezometric levels, the vertical ground displacements show larger amplitude for long term signal than for short one, indicating a behavior depending on the duration of the hydrogeological load. This difference of reactivity in time can be related to the heterogeneity of the studied aquifer. Finally, this work shows that geodetic measurements provide important constraints for characterizing aquifer-system response.

Highlights:

- Review of geodetic tools for hydrogeological survey
- GPS measurements of 3D deformation above a fractured aquifer
- Difference between long-term (seasonal) and short-term (few days) response of an aquifer

Keywords: Geodetic measurements, GPS, deformation, hydrogeology

I- Introduction

Many processes with various time and spatial scales are involved in the deformation of the Earth's surface. This complex deformation has been largely studied thanks to geodetic tools like GPS measurements, radar interferometry InSAR, tiltmeters or levelling. They have proved their great capability for tectonics and seismological studies at plate boundaries, where centimeter to meter ground surface displacements occurred and where relative velocities are significant. In most of these studies, horizontal deformations are dominant. More recently, geodetic methods were used to study load processes, like subsidence, ocean tide loading, atmospheric charge or hydrogeological processes related to water volume redistribution in the ground and the underground. These loading processes generate mainly vertical displacements from millimeter to decimeter that are also measurable with geodetic instruments, however with less accuracy compared to horizontal components in the case of GPS method. The study of the vertical deformation needs then some devoted strategies to extract small vertical displacements.

Ground surface deformations above deep porous reservoirs result from withdrawal or injection of fluids that first induce variations in pressure and effective stresses inside the reservoir and then a deformation of the reservoir that propagates to the overlying material. In the case of water reservoirs, the vertical displacements are significantly greater than the horizontal ones, contrary to gas or oil reservoirs where horizontal displacements are usually more pronounced (Teatini et al., 2011). Relations between compaction and effective stress can be established from the Terzaghi's principal, stating that a decrease of fluid pore pressure associated to withdrawal of fluids (i.e. an increase of the effective stress) induced a ground subsidence and reversely for an increase of pore fluid pressure. 3D elastic theory (Biot, 1941) or inelastic theory (Biot, 1973) and poroelasticity theory (Rice and Cleary, 1976) allow to derive the 3D displacement vector, as a function - in the case of hydrogeological studies – of the water head variations and of the hydromechanical properties of the aquifer like compressibility, elastic and poroelastic coefficient (Polland, 1984, Narasimhan, 2006). Note that the variation of the effective stress related to a given water level variation is usually larger in the case of a confined aquifer than in the case of an unconfined one (Hoffmann et al., 2003b), by consequences the studies related to hydrogeological ground deformation are in general limited to confined aquifers.

In this study, we focused about the deformation related to water level variations in aquifers. In this kind of application, the goal is to measure as precisely as possible the 3D ground surface deformation with the best spatial and time resolution as possible. This provides additional information on aquifers properties to hydrogeological studies. Several geodetic methods have been used to quantify ground surface deformation, depending on the specificities of each method. In particular, numerous studies have been done for a long time on land surface deformation related to hydrogeological variations due to human activities (Poland and Davis, 1969; Poland, 1972). In those cases, geodetic tools must be chosen for their good accuracy to measure vertical motions, a-priori greater than the horizontal ones, as stated by the theory. Land subsidence caused by water level variations of aquifer is largely described in geodetic studies and a review is presented here. The horizontal motions are most rarely taken into account. Nevertheless, the horizontal displacements are not so negligible (Helm, 1994) and, in order to better constrain the hydromechanical models of aquifers, it is necessary to quantify the 3D ground deformation with the most suitable geodetic method. GPS is one of the instruments able to measure accurate 3D displacement of discrete points, continuously in time. The precision of the horizontal components is better than of the vertical one, but a differential GPS setup inside a local network greatly improves the results in order to measure accurately both the horizontal and vertical motions related to pressure variations in an aquifer. Two kinds of GPS survey done on the Ploemeur aquifer in French Brittany are described and show the 3D-displacement time series obtained for two different origins of groundwater level variations, seasonal charge and discharge or pumping test.

II- Geodetic tools for hydrogeological deformation

Precise leveling was one of the first methods used to quantify the subsidence related to a ground-water withdrawal (Poland, 1984, Wilson and Gorelick, 1996). It requires the establishment of a network of benchmarks and a first survey by precise leveling. The difference with a second survey at a later time will give the displacement of each benchmark and then the deformation of the network. The resolution of this deformation map depends on the distance between benchmarks and the good accuracy of the data depends on various parameters but can be less than 1 mm. The disadvantage of this method is that the duration to achieve one survey can be long (at least few hours and sometimes few days) and this time increases with the number of benchmarks and on the size of the study area. During this time, new deformations can go on whereas one survey is assumed to correspond to the state of the ground at a given time.

Tiltmeter measurement of ground deformation was recently updated and improved with high-resolution tiltmeters (d’Oreye and Zurn, 2005, Boudin et al., 2008). Long-base tiltmeters measure a vertical displacement gradient from the variations of a liquid-level surface of a baseline up to 200 m long. Very small tilt angles can be measured with stability of 10^{-8}rad/month and accuracy better than 10^{-10} rad, continuously in time. This high sensitivity and this accuracy conduct to recent experiments in hydrogeological domain where the surface ground deformation related to water pressure variations in aquifer should be very small (Weise et al, 1999; Fabian and Kümpel, 2003; Longuevergne et al. 2009; Jacob et al, 2010). These studies show that tiltmeters are able to record very accurate value of vertical displacement gradient in real time and at a discrete position that can be related to instantaneous fluid migration in reservoirs. One disadvantage is that greater the baseline is, better the accuracy of the tilt angle is, but greater the determination of the absolute value of the vertical displacement is uncertain because the deformation is distributed all along the baseline. It should be noticed that all environmental noises are recorded and should be difficult to filter because of the high sensitivity of this instrument. Furthermore, the tiltmeters require very specific installation conditions, even more limiting for long baseline tiltmeters depending on field configuration.

Advances in space geodesy allow measurements of both horizontal and vertical deformation avoiding a part of problems related to field instrumentation. In particular, Interferometric Synthetic Aperture Radar (InSAR) leads to a lot of studies related to ground deformation since the development of this technique in 1992. By comparison between two satellite radar images acquired on a same area, but at different dates, InSAR provides map of the displacement of a thousand of square kilometers, with a spatial resolution of about few 10 m, with less than 1 centimeter relative displacement accuracy (Massonnet and Feigl, 1998; Rosen et al, 2000). Despite some limitations related to atmospheric conditions or spatial decorrelation in vegetated zones, many processing improvements like Permanent Scatterers (PS-InSAR, Ferretti et al, 2000; 2001) were developed that allow applications of this method in many areas. Furthermore, the database of SAR observations over 20 years allows compute multi-interferograms and time series of the deformation (Pritchard 2006; Simons and Rosen, 2007). For the oldest satellites (ERS, Envisat …) that can provide the deformation since the 1990s, t~~T~~hese time series have a minimum time sampling of 35 days corresponding to the repetitive paths of satellites while the revisit frequency is decreased to about 10 days with the new X-band satellites. In view of geodetic applications where 3D movements of the Earth's surface have to be characterized, it should be noticed that InSAR provides only one component of the displacement field, the Line of Sight Displacement (LOS), along the range direction from the satellite to the ground. Using both descending and ascending trajectories of satellite, it is possible to resolve accurately two components of the vertical and horizontal displacement. In the case of hydrogeological studies where deformations related to water withdrawal are mainly vertical, this limitation is not too constraining because the range direction is almost vertical and then more sensitive to the vertical motions. Then, most of the InSAR studies of seasonal ground deformation induced by a pumping or the recharge of an aquifer focused on the vertical displacement, with very accurate and high resolution results (Galloway et al, 1998; Amelung et al, 1999; Galloway and Hoffmann 2007; Bell et al, 2008; Gonzales and Fernandez, 2011), while horizontal displacements are often neglected (Hoffmann and Zebker, 2003a). Note that this is not in the case for gas reservoirs where horizontal deformations can be significant (Ketelaar et al., 2007; Tamburini et al. 2010; Teatini et al. 2011).

GPS is another space geodesy tool that allows measuring the 3D ground surface deformation with accuracy. Since implementing of this technique in the early of 1980s, this method was largely used to estimate the horizontal displacement rates especially at the plate boundaries. The accurate location results from a trilateration using satellites: the GPS receiver, i.e. the place to locate, being at the intersection between spheres centered on the satellites. In theory, only 4 satellites are needed to locate a receiver, i.e. to estimate the three coordinates X, Y, Z and time values. However, at least 6 satellites have to be included in the processing to remove or limit all the uncertainties. These later ones come from a lot of sources such the signal travel through the different layers of the atmosphere (troposphere and ionosphere), the time synchronization of receiver and satellite clocks, the accurate orbits of the satellites, and the signal multipath. GPS positioning accuracy can range from 5 m to 1 mm depending on various parameters. Geodetic high-precision positioning is achieved with sophisticated receivers measuring both pseudorange and carrier-phase, these measurements at two different frequencies allowing in addition to better calibrate the ionospheric delay (Blewitt, 2007). The parameters of field data acquisition and of post-processing are also of great importance to improve the precision. Differential corrections involve the use of a reference receiver at a known position to estimate the systematic GPS errors that can be removed from the measurement taken by remote receivers located at short distances of the reference. The distance classically recommended is lesser than 30 km, the differential correction being improved with baselines as short as possible. These corrections can be done in real time (correction data transmitted by different ways) or after a post-processing. A longest observation period is also an important parameter that increases the accuracy of post-processing data. Finally, common processing strategies have been defined for ground surface deformation measurements (Blewitt, 2007). In view of monitoring the ground surface deformation related to reservoir exploitation, one can obtained time series of the 3D-displacements with permanent GPS stations that can reach 1 mm precision for the horizontal components in the best setup, the vertical component being two or three times less accurate than the horizontal ones. Recent studies devoted to hydrogeological reservoirs where vertical ground movements are predominant, show that GPS is anyway a powerful tool to measure these displacements (Moreau et al., 2006; Burbey et al., 2006; Baldi et al., 2009; Hill et al, 2009; Zerbini, 2010; Biessy et al. 2011 Ji and Herring, 2012). These studies described centimeters vertical displacements with annual periodicity induced with seasonal cycle couple in some cases with regional deformation, such as in Po Plain (Teatini et al., 2005; Baldi et al., 2009). The GPS campaigns are commonly coupled with gravimetry surveys to refine the modeling of the effects of hydrological loading (Demoulin et al., 2007; Rosat et al., 2009). Different processing strategies were implementing that depend mainly on the size of the study area: local network with differential setup in case of small survey area (order of km), regional network in an absolute framework in case of large area (hundreds of km). Most of these studies highlight the need for time series shorter or longer depending on the hydrologic signal of interest, in order to better filter out other processes and to achieve the accuracy required to analyze the soil deformation induced by hydraulic loading variations.

All these geodetic instruments have their own characteristics and provide different kinds of information of the ground deformation: spatial or discrete data, time series or displacements at one time, horizontal and/or vertical components, absolute or relative displacements with different accuracies. Obviously, the best way to quantify the deformation of the land surface is to combine these different methods when possible (Watson et al., 2002; King et al., 2007; Motag et al., 2007; Muntendam-Bos et al, 2008). The case study presented in this paper is limited to GPS measurements. We focus the attention on the strategy to extract small vertical displacements and to show that horizontal displacements must be taken into account in order to characterize the flow direction into an aquifer from the 3D ground surface deformation. Results with other geodetic tools can be found in Bour et al (2007) and Moreau et al (2007).

III- Field survey with local GPS network

3.1 Site description

The Ploemeur aquifer is a well-studied hydrological research site, located in south coast of French Brittany (Fig. 1). This area is made up of crystalline fractured rocks that constitute a type of groundwater reservoirs with small dimensions. The Ploemeur site is characterized by a large pumping rate of 3000 m^3/days compared to the flow rates observed in the region. Most of the water flow is located in a highly heterogeneous zone, at the intersection between a flat contact dipping 30° to the north, separating a micaschist unit at the north to a late Hercynian granite at the south, and a late dextral fault zone striking N020° and dipping 70° to the east (Fig. 1) (Touchard (1999); Le Borgne (2007); Ruelleu et al. (2010)). The site includes three pumping wells and has a small extent of a few square-kilometers. Variations of piezometric levels are measured in many boreholes in an area 1 km around the pumping site and depend on the geological bedrock and on the distance to the pumping wells.

GPS measurements were conducted in order to estimate the ground deformation induced by the water level variations of this hydrogeological site. This area is characterized by low seismicity and high amplitude Ocean Tide Loading (OTL). OTL is the result of water masses transfer and periodic load of the ocean on the Earth's crust induced by tide cycle, producing local deformation on land surface (Farell, 1972). The flexure of the crust can reach several centimeters in coastal areas that are subject to large oceanic tides such as French Brittany and is recordable with geodetic instruments (Llubes et al., 2008). Considering these characteristics, we have supposed that very long term tectonic processes are negligible at the time scale of the study and the OTL deformation must be carefully filtered in the resulting deformation signal with an adapted field and processing setup. It must also be check that other loading phenomena do not remain in the final signal, which would then reflect only the local hydrological processes. For this reason, we used a network of GPS stations with very short baselines that is able to filter large-scale processes and to keep only local site phenomena (Hill et al., 2009).

Two types of results are shown. The first one concerns the continuous measurements of displacements during 3 years of the permanent MF1 GPS (Fig. 1). That shows the effect on the ground surface of the seasonal variations of the water level in the aquifer (long term experiment). The second one is to measure the effect of sudden pressure variations consecutive to a pumping test on the ground surface during ten days (short term experiment). For this experiment, a network of four GPS stations is used, including the MF1 permanent GPS station and three temporary GPS (F34, MF3 and F37 on Fig. 1). We will show that a comparable piezometric variation inside the aquifer induced different vertical displacements. In both experiments, horizontal displacements are smaller but measurable.

3.2 GPS data processing

Time series of the three components (North, East and Up) are obtained with the GAMIT scientific software (Herring et al., 2006). The data were processed with baselines between a survey station located on the pumping site and a fixed reference station located at 4.5 km to the study, i.e. outside the influence the aquifer (Fig. 1). International GNSS Service (IGS) final orbits are incorporated in the processing. We used the global mapping function (GMF) to model the troposphere. Most of the processing parameters are classically chosen: solid Earth tides, pole tides and high frequency tide corrections were applied following the IERS03 standards, as well as IGS antenna phase center models. The FES2004 OTL grid (Lyard et al., 2006) was used to interpolate OTL components from a global grid. The OTL effects are classically removed using such a model. The multipath perturbation is minimized thanks to the good quality of the emplacement of the GPS stations on the site, without plane surface close to the antenna receivers. The a priori constraints on the survey stations positions are 1m on the horizontal components and 2m on the vertical one. The long-period displacements were sampled with 24-h sessions, providing one position per day.

In order to minimize global effects and to increase the accuracy, a differential setup with short baselines (4.5 km in this study) has been used. It allows minimizing the ionospheric errors and Earth tides and OTL effects because presumably these phenomena are very similar between close receivers. Indeed, even if we applied an OTL model in our processing, it can be imperfect on very local scale (<10 km), especially in areas with high magnitude tide effects and important gradients such as Brittany (Melachroinos et al., 2007; Vergnolle et al., 2008; Llubes et al., 2008). Finally, we obtain baseline time series for each station pairs. One of the stations is supposed fixed so that these time series represents the displacements of the mobile station, with a processing accuracy between 1–3mm for the horizontal components and 5–7 mm for the vertical component. This assumption can be discussed since part of the deformation should be attributed to base station motions. This problem should be reduced by the use of a global network that allows really fixing the base station of the baseline in this reference network. But the global network can also be subject to deformations that are not entirely perfectly modeled at the scale of our study so that we choose not to link our data to a global network but to justify this fixed station with geologic arguments.

IV- Hydrogeological deformation at different time scales

4.1 Long term deformation

The results of this study have been discussed in Moreau et al (2006) and Biessy et al. (2011). We briefly describe the measurement and data processing protocol of the experiment, similar for the short term study, and we show the main results that will be used to compare with the short-term experiment.

The GPS survey started in April 2005, with a time sampling of 60 s. Data gaps are due to power supply perturbations or to various technical problems. The data recorded on the pumping site at the MF1 station are post-processed in a differential setup with corrections calculated thanks to the fixed EPUR reference station (Fig. 1), the details of the processing scheme being described in section III-3.2. The MF1 and EPUR stations are installed on tripods fixed on 50 cm depth concrete foundations. For all stations, the foundation cannot be anchored into the bedrock, which is too deep (more than 30 m). The EPUR station is located 4.5 km south of the pumping site, on a granite massif, with less fracturing and alteration than nearer the pumping site (Fig. 1). Based on these geological observations, this area seems to be disconnected from the hydrogeological influence of the Ploemeur aquifer. Moreover, we have shown in Biessy et al (2011) that the differential setup with this short baseline is able to remove Earth tides and OTL effects because they act in the same way at both receivers. The same argument is also valid for ionospheric loading and errors. Finally, thanks to the chosen configuration and to the processing strategy, we obtain a precision between 1–3mm for the horizontal components and 5–7mm for the vertical component, and mostly, it is possible to assign the final signal entirely to the displacement of the MF1 station resulting to local hydrological variations.

From the time series of the North, East and Up components of the MF1 displacement (Fig. 2), it was shown that the ground was submitted to 3D elastic deformation with sub-annual periodicities. It was then possible to infer a major direction of this 3D displacement that show a trend in the SSE-NNW with a southward steep slope that could correspond to the main direction of water flow inside the aquifer during the annual recharge/discharge cycle of the aquifer (Biessy et al, 2011). Moreover, the relationship between the ground deformation and the piezometric level into a confined aquifer is controlled by the hydromechanical properties of the system. The correlation between the two signals (Fig. 2) suggests that the variations of the hydraulic head inside the confined aquifer are the major process generating the observed ground deformation. In the Ploemeur aquifer, the annual variation of piezometric level is essentially controlled by seasonal charge and discharge of the aquifer while the anthropic effects of the pumping correspond to high frequencies components of the piezometric level (Fig. 2). If the change in effective stress is due solely to a change in fluid pressure or hydraulic head variations and not to a change in lithostatic stress, then a bulk storage coefficient can be calculated from the ratio between the variation of the vertical displacement and the variation of the hydraulic head. Details on this relation are given in Hoffmann et al, 2003b. From the GPS data and piezometric level of the Ploemeur aquifer, a storage coefficient of 2.10^{-3} was estimated, similar to those determined in previous independent studies (Moreau et al. 2006, Le Borgne et al. 2006). In the study area, the value of the storage coefficient implies an aquifer with a high volumetric compressibility, greater than the one expected for a crystalline area: the presence of a fractured zone modifies drastically the hydrogeological behavior of the host rock.

4.2 Short term deformation

In May 2006, a pumping test of 40 hours was conducted on the main pumping wells of the Ploemeur site in order to characterize the various geodetic variations related to a sudden and large variation of the pressure in the aquifer (Bour et al., 2007; Moreau et al., 2007). Following the continuous pumping of the site for several years, the pumping has been totally stopped that produced a sudden increase of piezometric levels in wells, up to 10 m at the principal pumping well PE, and around 5-6 m on the studied wells. This water upwelling produces water redistribution into the aquifer and consequently either mass variations that are likely to induce gravimetric variations above an unconfined aquifer or pressure variations that can generate ground deformation in the case of a confined aquifer. This kind of experiment should then be used to estimate the porosity or the hydromechanical properties of the ground. In the case of Ploemeur with a very complex structure of the aquifer, previous hydrogeological studies conclude that both confined and unconfined parts controlled the hydrological behavior of the system. In particular, the long term deformation experiment shows a typical behavior of a confined aquifer. In this study, we present only the deformation GPS data.

Like for the long term variation, the EPUR station was chosen as the fixed station while three other GPS stations were installed temporarily for ten days in order to register the hydrological deformation of the site, few days before the pumping test and few days after, in addition to the permanent MF1 station. GPS stations were located in an area of 200 m around the principal pumping well (PE on Fig.1), closed to boreholes where the piezometric levels are recorded (Fig.1).

4.2.1 Results on the MF1 station

As for the long term time series, we compute the deformation of the GPS stations located on the pumping site from the differential baseline formed with the EPUR station and with 24 hours sessions in order to increase the precision of the resulting time series (Fig. 3). A test with 6-hours sessions showed that the corresponding accuracy, 1 cm and greater on the vertical component, is not sufficient to detect the displacements of less than 2 cm expected from the results of the long term GPS series. For the MF1 station, the vertical deformation is shown on the figure 3, in comparison to the piezometric level of the adjacent well. All the boreholes around the principal pumping wells show the same behavior: at the beginning of the interruption of the pumping, the water level increase suddenly and then continue to increase more slowly until it seems to tend to reach an equilibrium. This final behavior cannot be observed on our data sets because the pumping was restarted before the equilibrium has been reached. In the well associated to the MF1 GPS station, the maximum piezometric variation reaches around 6 m during the 40 hours that the pumping was stopped (Fig. 3).

On the curve of the vertical daily solution, we observe a trend to a swell of the ground around the time of the stop of the pumping while a subsidence of the ground seems to exist after the restarting of the pumping. The amplitude of this deformation would be of the order of 5 mm. This result has to be taken into account with caution because this amplitude is of the same order than the precision of the time series. The trends can be observed but not confirmed.

In order to refine this result, we have computed a time series of the displacements, always with 24h sessions to maintain a good accuracy, but with a 1h shift of the 24h GPS data files. We obtained a vertical deformation time series with a point per hour (Fig. 3). This processing would be more able to detect the beginning of the pumping test on the deformation data, which is not possible with just a point per day. The comparison between the daily solution and the sliding window solution (Fig. 3) show that no significant difference exists and that no significant additional information appears on the series of sliding 24h-window. The high amplitude peaks that should firstly be assigned to the noise of the data in the daily series are also present in the sliding window series and all the growths and decays of the two curves are similar with no time shift. Finally, the simple daily solution corresponds to a smooth version of the sliding window solution.

The horizontal components are also displayed (Fig. 4). Considering that the maximum amplitude observed on both the North and the East components is less than 2 mm with a precision of 1-3 mm, we then conclude that there were no significant horizontal displacements during the time of the pumping test.

4.2.2 Results on the GPS network

The data processing of the four GPS stations near the pumping site is achieved with the same parameters and the same differential setup, with the EPUR station fixed (Fig. 1). The measured deformations of the four stations are comparable (Fig. 5). The variations of the horizontal components of the displacement do not exceed 1 or 2 mm, that confirm that there is no significant horizontal displacements registered on the site during the pumping test.

The vertical components of the displacement show greater amplitudes and similar trends on the four stations, with a growth of the displacement around the time of the interruption of the pumping and a decrease of the displacement that begins closely to the time of the restarting of the pumping. The amplitude of the up components during this period is of the same order of approximately 5 mm on all the GPS stations. This similar behaviour can be correlated to the similar piezometric levels of the adjacent boreholes. Only the amplitudes of the piezometric levels are different and are related to the distance from the pumping wells. The greatest value is observed at the MF3 well, which is the nearest from the main pumping well PE (Fig. 1). The water pressure variations are smaller at the F34 well which is the farthest from the main pumping well and located away from the altered N020° fault zone where major water flow occurs (Fig. 1), this zone being approximately defined by the elongation direction of the protection hydrological area (Fig. 1). With a variation of piezometric level lesser than 1 m, the deformation corresponding to the F34 well should be smaller than for the other wells. The 5 mm vertical displacement of F34, similar to the other wells, should be rather due to the 5-7 mm precision defined from the data processing. For all the GPS stations, the amount of vertical displacements is of the same order than this 5-7 mm precision. Thus the physical meaning of the signals and their interpretation could be questioned. Nevertheless, the major features of these signals are recovered in the same way by the four GPS receivers and then should represents a real signal associated to the pumping test, i.e. a swell of the ground associated to an increase of the water pressure in the aquifer and a subsidence corresponding to a decrease of water pressure. Therefore, the local GPS network with the short differential baselines seems to be sufficiently precise to record the deformations related to the pumping test. It should be noticed that GPS surveys are not able to register precisely the moment of the sudden pressure variations in the aquifer due to 24h-hour sessions. When it is required to detect instantaneously pressure variations in the aquifer, tiltmeters are better suited and give impressive results (Moreau et al., 2007; Jacob et al., 2010).

V- Comparison between long-term and short-term results

This work presents the behavior of the ground surface above a confined aquifer submitted to long term (tens of months) and short terms (tens of hours) solicitations. In the long-term case, the ground water level variations results from natural seasonal charge and discharge of the aquifer over the year (i.e. a slow variation) while in the short-term case, the water level variations result from a sudden pumping stop with effects lasting few days. The comparison between these two experiments is justified because the variations of hydraulic head of the aquifer are of similar amplitude, respectively 8 m and 6 m for solicitations of different origins. In the case of the long-term experiment, seasonal deformation is clearly measured by the MF1 permanent GPS station (Moreau et al, 2006), with sub-annual periods registered on the three components of the displacement (Biessy et al, 2011). This study reveals that hydrological loading generates significant horizontal movements, up to 1 cm, i.e. the half of the vertical displacement. This 3D displacement can be related to seasonal water head variations in the aquifer during the annual recharge/discharge cycle of the aquifer. The process is roughly reversal, so a first raw conclusion of an elastic behavior of the system is realistic. In more detail, surface hydrological phenomena like hydrous state of the soil have also been mentioned that could explain a small time offset between the piezometric growth and the ground uplift (Biessy et al, 2011).

The horizontal displacement shows a significative amplitude. It was clearly associated to the annual hydrological cycle because it displays the same annual periodicity as the vertical component. It means that the pressure variations inside the confined aquifer induce stresses with a significant horizontal component. If the aquifer is subhorizontal, only a horizontal gradient of pressure can generate stresses inducing horizontal ground displacements. This pressure gradient can be generated by the water flow inside the aquifer that is higher at one extremity. In our case, it could mean that the main annual water supply inside the confined aquifer comes from the south (Biessy et al., 2011). If the aquifer is inclined, the lithostatic pressure is smaller at shallow depth. Thus a same piezometric variation inside the whole aquifer will generate larger vertical deformation above the shallow part of aquifer than above the deep part. This horizontal gradient of deformation of the aquifer generates a horizontal displacement of the ground surface in addition to the vertical displacement. The resultant of the vertical and horizontal components can roughly estimate the dip of the aquifer. If this hypothesis is applied to the Ploemeur study, the measured deformation predicts a dip of the aquifer toward the North, which is compatible with the study of Ruelleu et al. (2010).

In the case of the short-term experiment, measured horizontal displacements are negligible in comparison to the precision of the time series. Furthermore, the reality of a deformation signal corresponding to the pumping test can be discussed because of the small amplitude of the vertical displacement compared to the accuracy of the data. But the correlation between the shapes of the curves of the four GPS stations leads us to believe that a real signal of the ground deformation exists induced by this short event. Then, considering that the ground surface deformation is reversal in both long-term and short-term experiment, the same kind of analysis than in the long-term experiment can be performed to define hydromechanical properties of the aquifer. In particular, if we consider vertical displacement of 5mm and correlate it to the 6 m piezometric variations, an elastic storage coefficient of 8.10^{-4} is obtained, significantly smaller than for the long term experiment. In detail, such a coefficient can be estimated for each place where a piezometer is coupled with a GPS: it results in a range from 3.10^{-4} to 8.10^{-3}, i.e. ratio of 10 between the extremes. This range points out the extreme spatial variability of the coupling between the ground deformation and the aquifer behavior. However, these values are significantly and systematically smaller than for the long- term experiment, which provided of a coefficient of 2.10^{-3}.

By consequence, the hydrogeological mechanisms involved in long-term and short-term solicitations of the aquifer appear to be different. This difference in behavior is not described in usual hydrogeological theory that uses simple geometry of confined aquifer with homogeneous elastic and poroelastic properties. A more complete model should take into account the complexity of a fractured aquifer like the studied one. The compartments of the underground involved during the charge and discharge of the aquifer in the long-term experiment are certainly different than these affected by a pumping test limited to few days. Indeed, the annual water supply should involve a wide zone (probably the whole aquifer) while a short pumping test mobilizes a more restricted area which size depends on the duration of the solicitation. The paths of fluid flows in this kind of highly complex aquifer are very difficult to identify and requires a very dense network of hydrogeological instruments. Despite numerous measurements on this experimental site, the heterogeneity of the underground does not allow to constrain all the hydrogeological parameters of this fractured water reservoir. However, it reveals a main heterogeneity of these parameters, and thus a pattern of the aquifer emphasized by the fracturation.

VI- Conclusions

This study shows that geodetic measurements are powerful tools to monitor ground surface deformation related to water level variations in a confined aquifer. In case of small deformation like in the studied aquifer, two GPS surveys corresponding to different time scales of hydrogeological solicitation are presented. 3D time series of displacements at discrete points are obtained. As stated in the review part of this work, this study should be completed to combine various geodetic methods, each of them providing additional information with a different degree of precision. To survey sudden charge and discharge of an aquifer in the case of a short term experiment, the sensitivity of tiltmeters is very well adapted to detect instantaneously pressure variations in the aquifer. In the case of the long-term seasonal deformation of an aquifer, it would be very pertinent to measure the spatial extension of the hydrogeological deformation with InSAR data since the beginning of the water exploitation.

GPS survey and processing setup must be adapted to extract, in particular, small vertical displacement associated to aquifer subsidence because of the lower accuracy of the measurement of this component by GPS. In this study, we chose a differential setup with short baselines in a local network. This survey strategy associated with an adapted data processing provides accurate time series of the three components of the displacement. Furthermore, this strategy allows global processes to be filtered. This point must be treated carefully in the studied Ploemeur aquifer, located in the Brittany region where the Ocean Tide Loading is of high amplitude. It has been checked by frequency analysis of time series of various time sampling and length (Biessy et al 2011) that only local effects, especially hydrological effect, remain in the final signal. It should be noticed that, reversely, this kind of local process has to be filtered in studies devoted to other deformation processes.

This GPS setup has been validated on the long-term study of the deformation related to seasonal charge and discharge of the Ploemeur aquifer. The measured vertical displacement has been clearly correlated to piezometric variations and allows estimating hydromechanical parameters of the aquifer. A less expected conclusion is that hydrogeological loading can generate significant horizontal displacements, the 3D resultant surface displacement being related to the water flow direction. The same GPS protocol was then used to record the ground deformation following a sudden water level variation induced by a pumping test. The GPS time series show that horizontal displacements are negligible and that vertical displacements are small compared to the accuracy of the data but seems significant. For comparable piezometric variations of the aquifer, the amplitude of the vertical displacement for the short term and for the long term experiment are different with a ratio up to 4. This conducts to different estimations of the storage coefficient of the aquifer, depending on the time scale of the solicitation. This is attributed to the high complexity of the Ploemeur fractured aquifer where local estimate of hydromechanical parameters is not representative of the heterogeneous underground. The theory governing the ground deformation related to exploitation of porous reservoirs with simplified geometry is relatively well understood and allows a characterization of hydromechanical and migration properties from measurements of ground surface displacements. In the case of complex fractured reservoirs, further advances in numerical modeling of such media are necessary in order to better integrate the 3D-displacements of the ground surface now available from geodetic measurements.

Acknowledgements

We thank O. Bour for the helpful discussions in the understanding of hydrogeological settings of the experimental site of Ploemeur and for the data of piezometric levels. G. Biessy participated to the data processing of short-term experiment. This work has been supported by ANR Hydrogeodesy, ORE RENAG and ORE H+.

VII- References

Amelung, F., Galloway, D.L., Bell, J.W., Zebker, H.A., Laczniak, R.J., 1999. Sensing up and downs of Las Vegas: InSAR reveals structural control of land subsidence and aquifer system deformation. Geology 27, 483–486.

Baldi, P., Casula, G., Cenni, N., Loddo, F., Pesci, A., 2009. GPS-based monitoring of land subsidence in the Po Plain (Northern Italy). Earth Planet. Sc. Lett. 288(1-2), 204–212.

Bell, J. W., Amelung, F., Ferretti, A., Bianchi, M., Novali, F.,2008. Permanent scatterer InSAR reveals seasonal and long-term aquifer-system response to groundwater pumping and artificial recharge. Water Resour. Res. 44, W02407, doi:10.1029/2007WR006152.

Biessy, G., Moreau, F., Dauteuil, O., Bour, O., 2011. Surface deformation of an intraplate area from GPS time series. J. of Geodyn. 52(1), 24-33, 10.1016/j.jog.2010.11.005.

Biot, M.A., 1941. General theory of three-dimensional consolidation. J. Appl. Phys. 12, 155-164.

Biot, M. A., 1973. Nonlinear and semilinear rheology of porous solids. J. of Geophys. Res. 78(23), 4924-4937.

Blewitt, G., 2007. GPS and Space Based Geodetic Methods, in: Herring, T., Schubert, G. (Eds), Treatise on Geophysics, Academic Press, Oxford, UK, Vol. 3., pp. 351-390, ISBN: 0-444-51928-9.

Boudin, F., Bernard, P., Longuevergne, L., Florsch, N., Larmat, C., Courteille, C., Blum, P.-A., Vincent, T., Kammentaler, M., 2008. A silica long base tiltmeter with high stability and resolution. Rev. Sci. Instrum., 79, doi:10.1063/1.2829989.

Bour et al., 2007. A field experiment to monitor the gravimetric and geodetic changes during a large-scale pumping test in a crystalline aquifer. Geophys. Res. Abstracts, Vol. 9, 07317, SRef-ID: 1607-7962/gra/EGU2007-A-07317.

Burbey, T.J., 2006. Three-dimensional deformation and strain induced from municipal pumping, Part 2: Numerical analysis. J of Hydrology, v. 330, p. 442-434.

Demoulin, A., Ducarme, B., Everaerts, M., 2007. Seasonal height change influence in GPS and gravimetric campaign data. J. of Geodyn. 43(2), 308-319.

D'Oreye, N. F., Zurn, W., 2005. Very high resolution long-baseline water-tube tiltmeter to record small signals from Earth free oscillations up to secular tilts, Rev. Sci. Instrum. 76(2), 024501.

Fabian, M., Kümpel, H.J., 2003. Poroelasticity: Observations of anomalous near surface tilt induced by ground water pumping, J. Hydrol. 281-3, 187–205, doi:110.1016/S0022-1694(1003)00234-00238.

Farrell W.E., 1972. Deformation of the earth by surface loads, Rev. Geophys. Space Phys. 10, 761–797.

Ferretti, F., Prati, C., Rocca, F., 2000. Nonlinear subsidence rate estimation using permanent scatterers in differential SAR Interferometry. IEEE T. Geosci. Remote Sensing 38(5), 2202-2212 .

Ferretti, F., Prati, C., Rocca, F., 2001. Permanent scatterers in SAR Interferometry. IEEE T. Geosci. Remote Sensing, 39(1), 8-20.

Galloway, D.L., Hudnut, K.W., Ingebritsen, S.E., Phillips, S.P., Pelzer, G., Rogez, F., Rosen, P.A.,1998. InSAR detection of system compaction and land subsidence, Antelope Valley, Mojave Desert, California. Water Resour. Res. 34, 2573-2585.

Galloway, D.L., Hoffmann, J., 2007. The application of satellite differential SAR interferometry-derived ground displacements in hydrogeology. Hydrogeol. J. 15(1), 133–154.

González, P.J., Fernández, J., 2011. Drought-driven transient aquifer compaction imaged using multitemporal satellite radar interferometry, Geology, 39(6), 551-554, doi:10.1130/G31900.1.

Helm, D.C., 1994. Horizontal movement in a Theis-Theim confined system: Water Resources Research, v. 30, 953-964.

Herring, T.A., King, R.W., McClusky, S.C., 2006, Gamit Reference Manual, Release 10.3.

Hill, E.M., Davis, J.L., Elosegui, P., Wernicke, B.P., Malikowski, E., Niemi, N.A., 2009. Characterization of site specific GPS errors using a short-baseline network of braced monuments at Yucca Mountain, southern Nevada, J. Geophys. Res., 114, B11402, doi:10.1029/2008JB006027.

Hoffmann, J., Zebker, H.A., 2003a. Prospecting for horizontal surface displacements in Antelope Valley, California, using satellite radar interferometry. J. Geophys. Res. 108, 6011, doi:10.1029/2003JF000055.

Hoffmann, J., Leake, S.A., Galloway, D.L., Wilson, A.M., 2003b. MODFLOW-2000 ground-water model-user guide to the subsidence and aquifer-system compaction (SUB) package. USGS Open-File Rep 03-233. http://pubs.usgs.gov/of/2003/ofr03-233/.

Jacob, T., Chéry, J., Boudin, F., Bayer R., 2010. Monitoring deformation from hydrologic processes in a karst aquifer using long-baseline tiltmeters. Water Resour. Res., 46, W09542, doi:10.1029/2009WR008082.

Ji, K. H., Herring, T.A., 2012. Correlation between changes in groundwater levels and surface deformation from GPS measurements in the San Gabriel Valley, California, Geophys. Res. Lett., 39, L01301, doi:10.1029/2011GL050195.

Ketelaar G., van Leijen F., Marinkovic P. and Hanssen R., 2007.Multi-Track PS-InSAR: Datum Connection and Reliability Assessment, In H. Lacoste & L. Ouwehand (Eds.), Proceedings of Envisat Symposium, Montreux, Switzerland, 23-27 April 2007 (pp. 1-6).

King, N. E., et al., 2007. Space geodetic observation of expansion of the San Gabriel Valley, California, aquifer system, during heavy rainfall in winter 2004–2005, J. Geophys. Res., 112, B03409, doi:10.1029/2006JB004448.

Llubes M. et al, 2008. Multi-technique monitoring of ocean tide loading in northern France, C. R. Geosc. 340(6), P.379-389 10.1016/j.crte.2008.03.005.

Longuevergne, L., Florsch, N., Boudin, F., Oudin, L., Camerlynck, C., 2009. Tilt and strain deformation induced by hydrologically active natural fractures: application to the tiltmeters installed in Sainte-Croix-aux-Mines observatory (France). Geophys. J. Int. 178, 667–677. doi: 10.1111/j.1365-246X.2009.04197.x

Lyard, F., Lefevre, F., Letellier, T., Francis, O., 2006. Modeling the global ocean tides: modern insights from FES2004. Ocean Dyn. 56, 394–415.

Massonnet, D., Feigl K.L., 1998. Radar interferometry and its application to changes in the Earth's surface. Rev. Geophys. 36, 441-500.

Melachroinos, S.A., Biancale, R., Llubes, M., Perosanz, F., Lyard, F., Bouin, M.-N., Masson, F., Nicolas, J., Morel, L., Durand, S., 2007. Ocean tide loading (OTL) displacements from global and local grids: comparisons to GPS estimates over the shelf of Brittany, France. J. Geod., doi:10.1007/s00190-007-0185-6.

Moreau, F., Dauteuil, O., Bour, O., Gavrilenko, P., 2006. GPS measurements of ground deformation induced by water level variations into a granitic aquifer (French Brittany). Terra Nova 18, 50–54.

Moreau et al., 2007. Vertical ground deformation monitored during a large-scale pumping test in a crystalline aquifer: comparison of several geodetic measurements. Geophys. Res. Abstracts, Vol. 9, 09125, SRef-ID: 1607-7962/gra/EGU2007-A-09125.

Motagh, M., Djamour, Y., Walter,T.R., Wetze,H.U., Zschau, J., Arabi, S., 2007. Land subsidence in Mashhad Valley, northeast Iran: Results from InSAR, levelling and GPS. Geophys. J. Int. 168(2), 518–526, doi:10.1111/j.1365-246X.2006.03246.x.

Muntendam-Bos, A.G., Kroon, I.C. ,Fokker, P.A., 2008. Time-dependent Inversion of Surface Subsidence due to Dynamic Reservoir Compaction, Math. Geosciences, 40(2), 159-177, DOI: 10.1007/s11004-007-9135-3

Narasimhan, T.N., 2006, Coupled equations for transient water flow, heat flow, and deformation in hydrogeological systems, J. Earth System Sci., 115(2), 219-228.

Poland, J.F., Davis, G.H., 1969. Land subsidence due to withdrawal of fluids. Geol. Soc. Am. Rev. Eng. Geol. 2, 817–829.

Poland, J.F., 1972, Subsidence and its control. In: Underground Waste Management and Environmental Implications. American Association of Petrology and Geology, Mem. No. 18, pp. 50–71.

Poland J.F., 1984. Guidebook to studies of land subsidence due to ground-water withdrawal, Paris, UNESCO, Studies and reports in hydrology, 40, 305p.

Pritchard M.E., 2006. InSAR, a tool for measuring Earth`s surface deformation, Phys. Today 75, 68-69.

Rice, J.R., Cleary, M.P., 1976. Some basic stress-diffusion solutions for fluid-saturated elastic porous media with compressible constituents, Rev. Geophys. Space Phys. 14, 227-241.

Rosat, S., Boy, J.-P., Ferhat, G., Hinderer, J., Amalvict, M., Gegout, P., Luck, B.. 2009. Analysis of a 10-year (1997–2007) record of time-varying gravity in Strasbourg using absolute and superconducting gravimeters: New results on the calibration and comparison with GPS height changes and hydrology. J. of Geodyn., 48(3–5), 360-365.

Rosen, P.A, Hensley, S., Joughin, I.R., Li, F.K., Madsen, S.N., Rodriguez, E., Goldstein, R.M., 2000. Synthetic aperture radar interferometry. Proc. IEEE 88(3), 333-382.

Ruelleu, S., Moreau, F., Bour, O., Gapais, D., Martelet, G., 2010. Impact of gently dipping discontinuities on basement aquifer recharge: an example from Ploemeur (Brittany, France). J. Appl. Geophys. 70 (2), 161–168.

Simons, M., Rosen P., 2007. Interferometric Synthetic Aperture Radar Geodesy, in: Herring, T., Schubert, G. (Eds), Treatise on Geophysics, Academic Press, Oxford, UK, Vol. 3., pp. 391-446, ISBN: 0-444-51928-9.

Tamburini, A., Bianchi, M., Giannico, C., and Novali, F., 2010. .Retrieving surface deformation by PSInSAR(TM) technology: A powerful tool in reservoir monitoring, Int. J. Greenhouse Gas Control, doi:10.1016/j.ijggc.2009.12.009.

Teatini, P., et al., 2011. Geomechanical response to seasonal gas storage in depleted reservoirs: A case study in the Po River basin, Italy. J. Geophys. Res., 116, F02002, doi:10.1029/2010JF001793.

Teatini P., Tosi L., Strozzi T., Carbognin L., Wegmuller U. and Rizzetto F., 2005. Mapping regional land displacements in the Venice coastland by an integrated monitoring system, Remote Sens. Environ., 98(4), 403-413.

Terzaghi, K., 1923. Die berechnung der durchlassigkeitzifer des tones aus dem verlauf der hydrodynamischen spannungserscheinungen. Akademie der Wissenschaften, Mathematish-naturwissenschaftliche, Klasse,Vienna, Part IIa, vol. 132, pp. 125-138.

Vergnolle, M., Bouin, M.-N., Morel, L., Masson, F., Durand, S., Nicolas, J., Melachroinos, S.A., 2008. GPS estimates of ocean tide loading in NW-France: determination of ocean tide loading constituents and comparison with a recent ocean tide model. Geophys. J. Int., doi:10.1111/j.1365-246X.2008.03734.x.

Watson, K.M., Bock, Y., Sandwell,D.T., 2002. Satellite interferometric observations of displacements associated with seasonal groundwater in the Los Angeles basin. J. Geophys. Res., 107, 2074, doi:10.1029/2001JB000470.

Weise, A., Jentzsch, G., Kiviniemi, A., Kaariainen J., 1999. Comparison of long-period tilt measurements: results from the two clinometric stations Metsahovi and Lohja, Finland. J. Geodyn. 27(2), 237–257.

Wilson, A.M., Gorelick, S., 1996. The effects of pulsed pumping on land subsidence in the Santa Clara Valley, California. J. Hydrol. 174, 375–396.

Zerbini, S., Raicich, F., Richter, B., Gorini, V., Errico, M., 2010. Hydrological signal in heights and gravity in northeastern Italy inferred from principal components analysis. J. Geodyn. 49, 190–204.

Figure Captions

Figure 1: Geological framework of the Ploemeur site and location of the base station EPUR and of the pumping site. In the zoomed map, the network of permanent and temporary GPS stations associated to piezometers is located. The protection hydrologic area is limited by the continuous line.

Figure 2: Time series of the North, East and Up displacements of the MF1 station and piezometric level of the associated well. The arrow indicates the date of the short term experiment.

Figure 3: Daily and sliding solutions (see text) of the vertical displacement of the MF1 station and piezometric level (dashed curve) of the associated well. Pumping was stopped during the period indicated by the gray band.

Figure 4: North (X), East (Y) and Up (Z) displacements (continuous curves) of sliding daily solution of the MF1 station (see text) and piezometric level (dashed curve). Pumping was stopped during the period indicated by the gray band.

Figure 5: North (X), East (Y) and Up (Z) daily displacements (continuous curves) of the four stations of the local GPS network of the pumping site and piezometric levels of the associated wells (dashed curves). Pumping was stopped during the period indicated by the gray band.

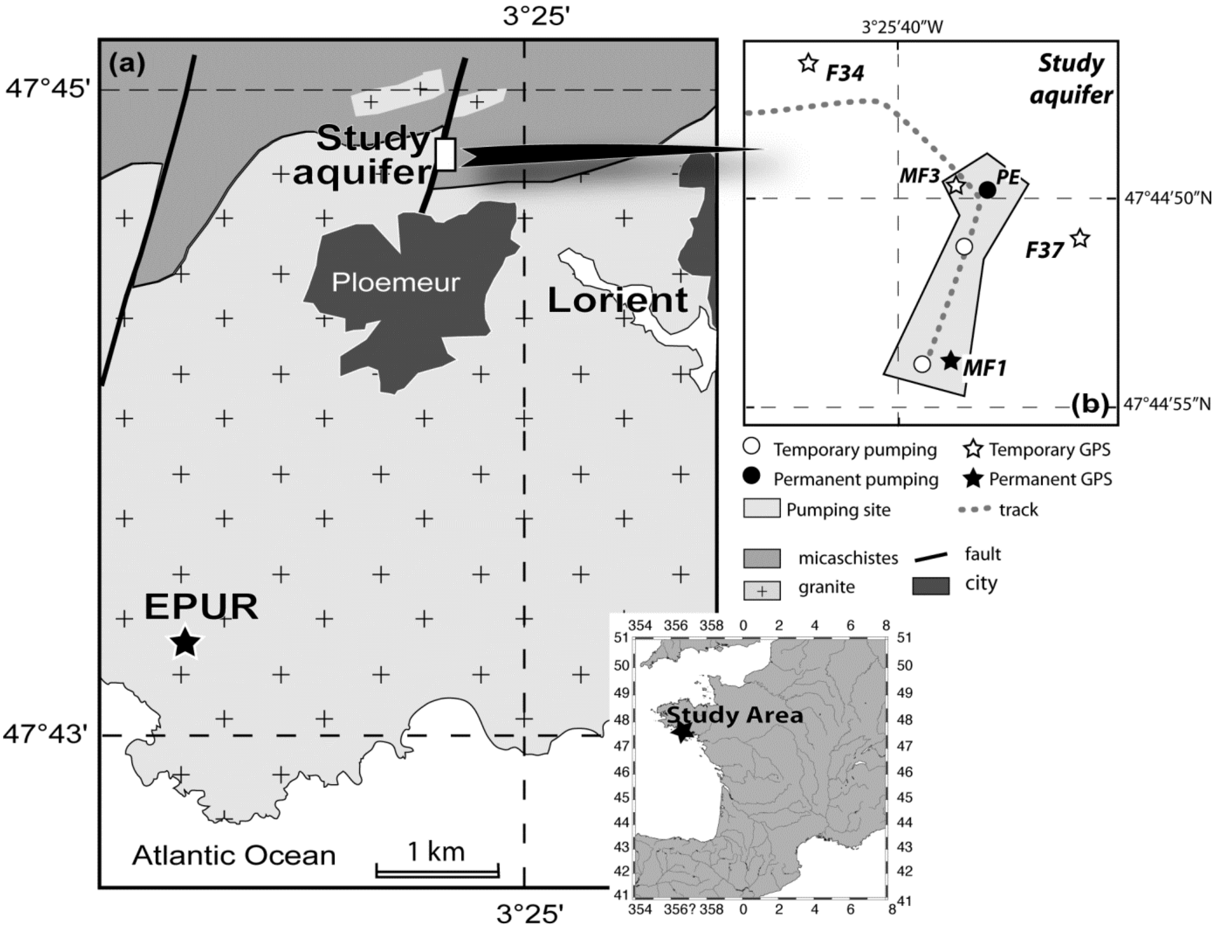

3°25'
(a)
47°45'
Study
aquifer
Ploemeur
Lorient
EPUR
47°43'
Atlantic Ocean
1 km
3°25'
3°25'40"W
Study
aquifer
F34
MF3
PE
47°44'50"N
F37
MF1
(b)
47°44'55"N
○ Temporary pumping
☆ Temporary GPS
● Permanent pumping
★ Permanent GPS
Pumping site
track
micaschistes
fault
granite
city
354 356 358 0 2 4 6 8
51 50 49 48 47 46 45 44 43 42 41
Study Area
354 356? 358 0 2 4 6 8

Figure 1

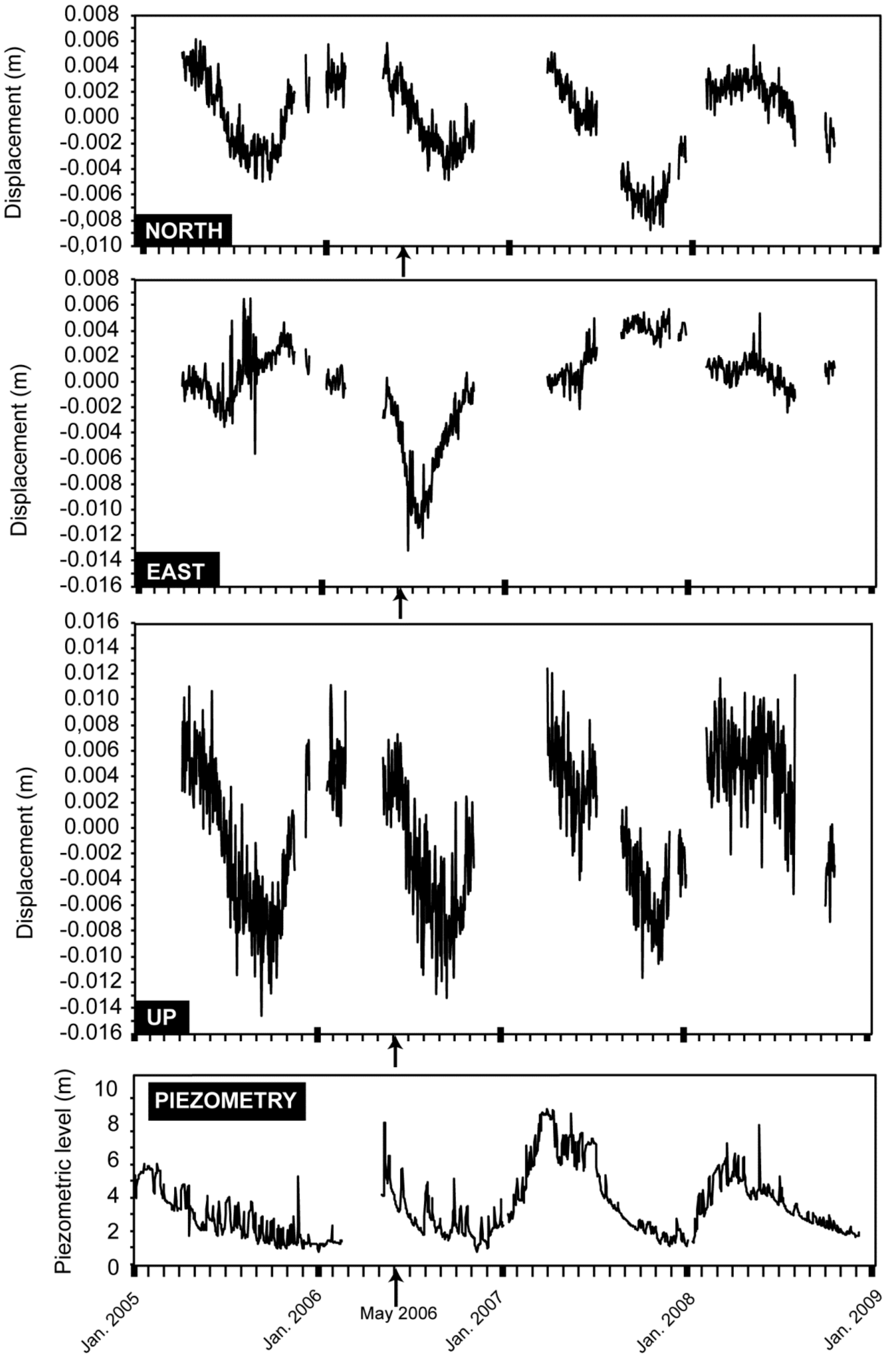
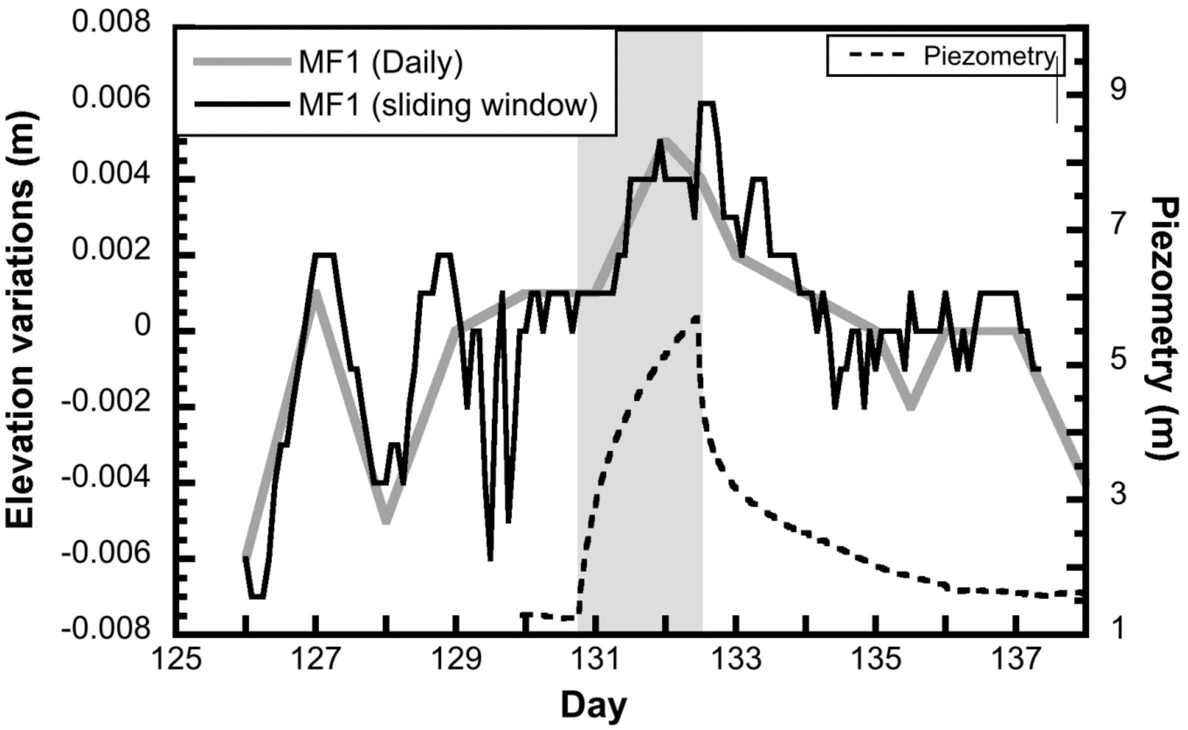

Displacement (m)
0.008
0.006
0.004
0.002
0.000
-0.002
-0.004
-0.006
-0,008
-0,010
NORTH
Displacement (m)
0.008
0.006
0.004
0.002
0.000
-0.002
-0.004
-0.006
-0.008
-0.010
-0.012
-0.014
-0.016
EAST
Displacement (m)
0.016
0.014
0.012
0.010
0,008
0.006
0.004
0.002
0.000
-0.002
-0.004
-0.006
-0.008
-0.010
-0.012
-0.014
-0.016
UP
Piezometric level (m)
10
8
6
4
2
0
PIEZOMETRY
Jan. 2005
Jan. 2006
May 2006
Jan. 2007
Jan. 2008
Jan. 2009

Figure 2



MF1 (Daily)
MF1 (sliding window)
Piezometry
Elevation variations (m)
0.008
0.006
0.004
0.002
0
-0.002
-0.004
-0.006
-0.008
Piezometry (m)
9
7
5
3
1
125
127
129
131
133
135
137
Day

Figure 3

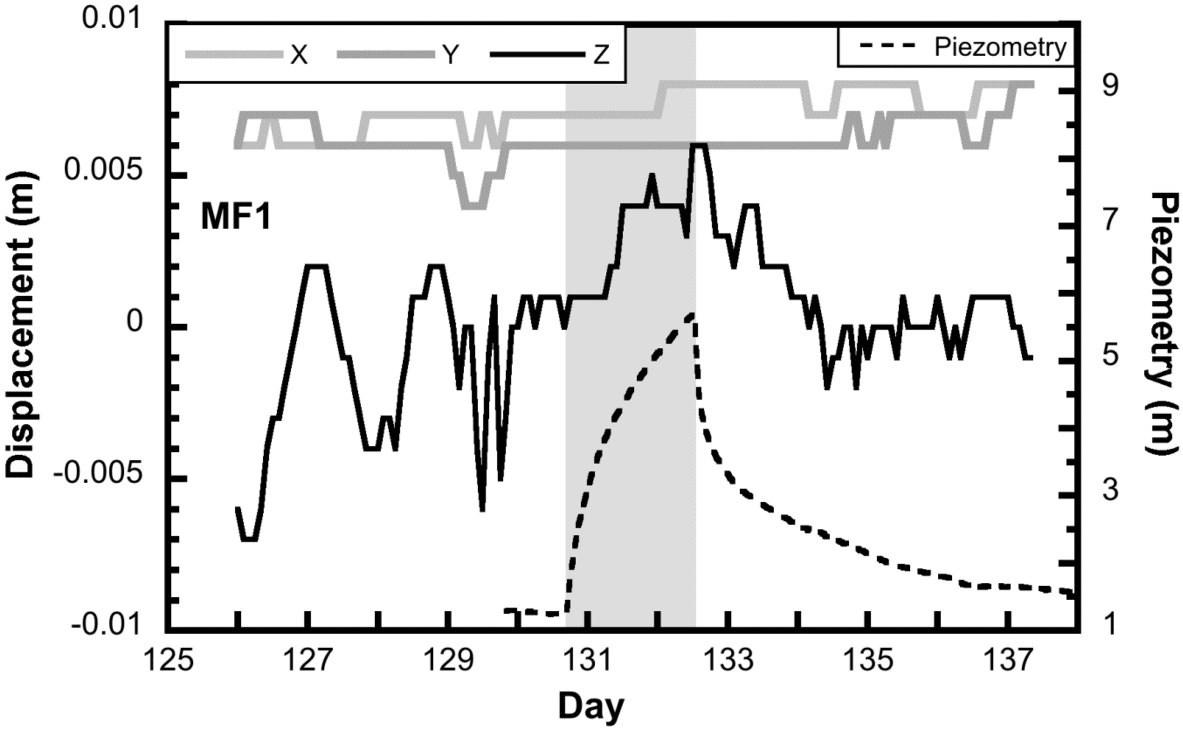

X
Y
Z
Piezometry
MF1
Displacement (m)
0.01
0.005
0
-0.005
-0.01
Piezometry (m)
9
7
5
3
1
125
127
129
131
133
135
137
Day

Figure 4

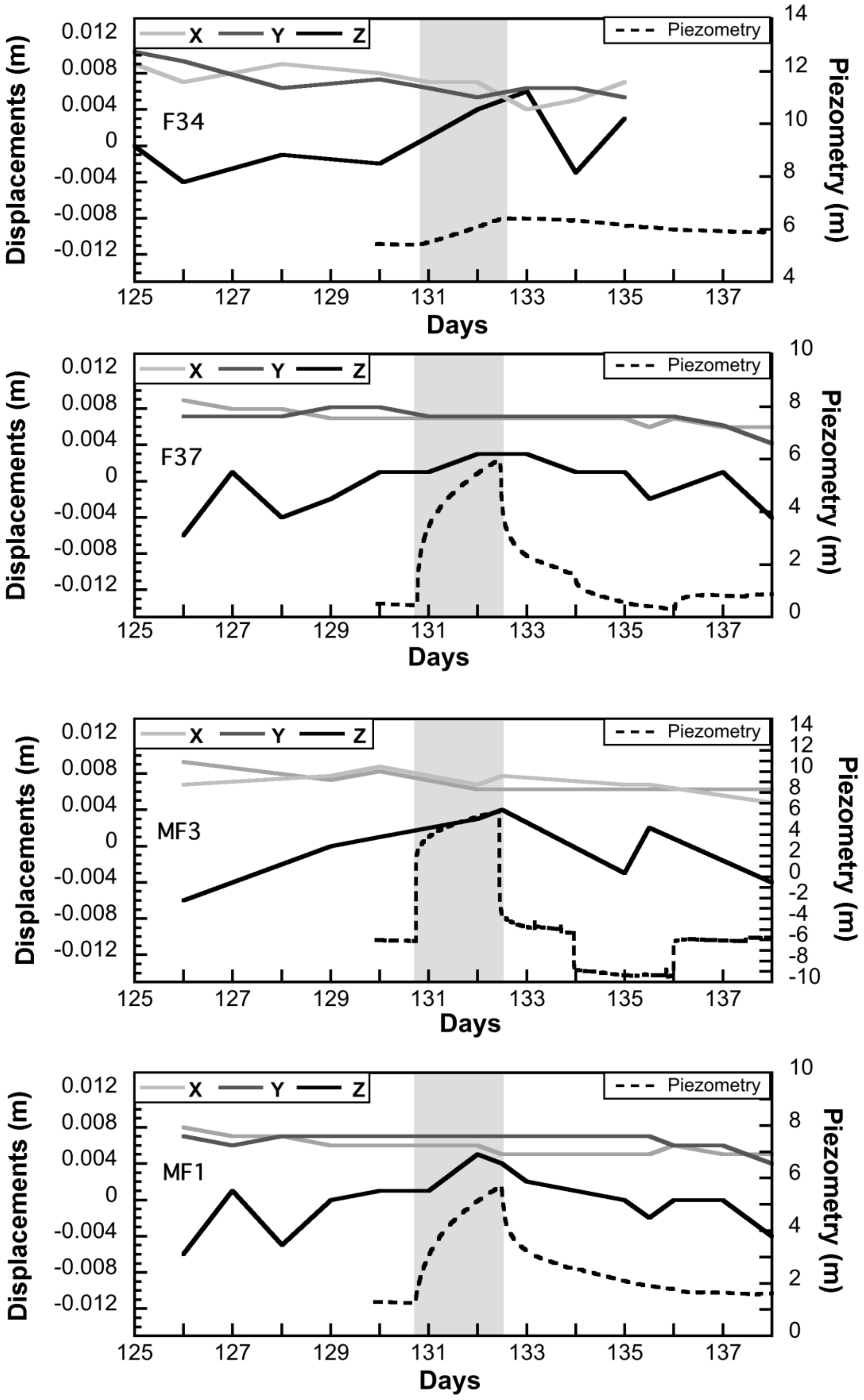

F34
F37
MF3
MF1
X
Y
Z
Piezometry
Displacements (m)
Piezometry (m)
Days
0.012
0.008
0.004
0
-0.004
-0.008
-0.012
125
127
129
131
133
135
137
14
12
10
8
6
4
2
0
-2
-4
-6
-8
-10

Figure 5