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Local hydrology, the Global Geodynamics Project and CHAMP/GRACE perspective: some case studies

M. Llubes[a,*], N. Florsch[b], J. Hinderer[c,d], L. Longuevergne[b], M. Amalvict[c]

[a] *LEGOS/CNES/CNRS, 18 avenue Edouard Belin, 31401 Toulouse Cedex 9, France*
[b] *UMR 7619 "Sisyphe", UPMC, 4 Place Jussieu, 75252 Paris Cedex 05, France*
[c] *EOST-IPGS (UMR 7516 CNRS/ULP), 5 rue Descartes, 67084 Strasbourg Cedex, France*
[d] *NASA GSFC Greenbelt, MD 20771, USA*

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Abstract

We first quantify the influence of aquifers on gravity variations by considering local, regional and continental scales. We show that locally only the direct attraction of the underlying aquifer has to be taken into account. At continental (or global scales), the underground water masses act by direct attraction (due to the earth curvature), loading flexure and potential redistribution. We show that at the intermediate regional scale (saying a few kilometres to a few hundreds of kilometres), groundwater contributions can be neglected in practice. Afterwards, we illustrate the difficulties in tackling the local hydrological context by studying comparatively the geological and hydrogeological surroundings of three European Global Geodynamics Project (GGP) superconducting gravimeter stations (Strasbourg, Moxa, and Vienna). Finally, it appears clearly that hydrological variability and cycle characterisations constitute the up-to-date challenge while studying gravity variations in a large spectral range. That is why, gravity is used to quantify hydrological transfers, and overall when seeking for small signals from the Earth's deep interior or other environmental signals (atmosphere, oceans) where groundwater influence can be seen as a disturbance.

1. Introduction

The gravimetry research community gathered within the Global Geodynamics Project (GGP) is interested in temporal variations of the Earth's gravity field and by the associated geodetic aspects, through

* Corresponding author. Tel.: +33 5 6133 2862; fax: +33 5 6125 3505.
E-mail address: muriel.llubes@notos.cst.cnes.fr (M. Llubes).

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the combination of data from superconducting gravimeters (SGs), with a variable geographic distribution over the Earth. Several disciplines and topics are involved; the synthesis paper in EOS by Crossley et al. (1999) describes, in a comprehensive overview, the various GGP challenges.

At the same time, new satellite gravity missions with low altitude satellites—typically 400 km for the CHAMP and GRACE missions—are dedicated to the study of the gravity field from space, and to its temporal variations. Such studies are helping to renew interest in gravimetry as a fundamental tool for the study of the Earth. This is due to the implications of high quality gravity information for large set of phenomena, involving modifications in the density distribution inside the Earth or in the surface layers (oceans, atmosphere, and hydrosphere) that produce measurable variations from periods of hours to years.

It is meaningful to ask how to inter-compare gravity data from ground-based measurements and from space, particularly the observations provided by the recently launched gravity satellites. In geodesy, the vertical displacements of the crust are phenomenologically associated with variations of the gravity field (geometrical coupling). The hydrological problem has to be addressed as soon as we are interested in measuring surface gravity variations or crustal displacements (Mangiaroti et al., 2001) that appear near the accuracy limit of available instruments (gravimeters and positioning system with geodetic quality). Hydrology is in fact a prime target of the new satellite missions dedicated to the study of gravimetry (CHAMP and GRACE), the main objective being the observation of water storage variations (Rodell and Famiglietti, 1999; Velicogna et al., 2001), identified from space from the induced attraction and flexural effects. From other points of view, the hydrological loading constitutes a “parasite signal”, e.g. in the study of vertical movements induced by tectonic stresses (Van Dam et al., 2001a,b), for the study of deep origin phenomena (motions and dynamics of the core) or when the aim is to interconnect gravimetric stations (establishment of a fundamental gravimetric network). Second, the study of gravity field variations allows us to estimate some hydrogeological parameters (e.g. efficient porosity) at a meso-scale that is not easily accessible from the ground alone.

In this paper, we first review several theoretical aspects concerning the influence of an aquifer on gravity, then we give a brief description of the hydrogeological environment for three European stations of the GGP, pointing out the very large variability of these environments and the need to improve the hydrogeological and hydrological studies around the SGs or stations with repeated measurements by absolute gravimeters.

2. The effect of aquifer variability on gravity

The analysis of space and time variations of parameters such as run-off, precipitation and groundwater levels involves a wide diversity in the characteristic scales which are involved in hydrology (Skoien et al., 2003; Neuman and Di Frederico, 2003). To study the effects of an aquifer on gravity, it is useful to distinguish three different scales:

- a local scale, for water masses located at distances up to 1–10 km, denoted L1;
- a regional scale, located in a ring between the local limit L1 and a more distant limit L2 (typically several 100 km). As we will see, the water enclosed in this area has a minimal influence on the gravity field at the current instrument level sensitivity, either by direct attraction influence or flexure;
- a global – or at least continental – scale, where only the water masses beyond the L2 limit are taken into account, because they will have a perceptible effect on the observations.

2.1. Local scale, L1

We first consider the first scale in stake (for distances to the station less than L1 = 1 or 10 km), by estimating the direct local attraction effect. It is shown later that the flexure and mass redistribution effects are negligible at this scale and hence have not to be addressed here.

To take into account the existence of underground water stored immediately beneath the gravimeter, a simple model based on a centred cylinder with a radius r, a thickness t and whose upper limit would be at depth d, can be used. We obtain for the attraction contribution:

$$\Delta g = 2\pi G\rho_w \left[t + \sqrt{d^2 + r^2} - \sqrt{(d+t)^2 + r^2} \right] \tag{1}$$

while r becomes large compared to t and d, this quantity quickly tends to the classical Bouguer's contribution corresponding to a horizontal and homogeneous layer (a sheet)

$$\Delta g_{\mathrm{Bouguer}} = 2\pi G\rho_w t$$

In other words, the term $\Delta g_{\mathrm{Bouguer}} - \Delta g$, relative to an horizontal ring beyond the distance r, becomes rapidly negligible as r increases, and there is little error in assigning the effect of local attraction to $\Delta g_{\mathrm{Bouguer}}$ as a first (and good) approximation.

When considering a more generic layer with a variable thickness $t(x, y)$, described by two interfaces, upper and lower limits $z_1(x, y)$ and $z_2(x, y)$, their heights being defined from a reference level h_0 (above the irregular layer), we can write the induced attraction using the formula given by Parker (1972):

$$\mathrm{FT}(g_z) = 2\pi G e^{|k|h_0} \sum_{n=1}^{\infty} \frac{(-|k|)^{n-1}}{n!} \mathrm{FT}[\rho(z_1^n - z_2^n)] \tag{2}$$

where FT is the Fourier transform of the quantity in square brackets [], G the constant of gravitation, k the spatial wave number, and ρ is the density in kg m^{-3}.

Even with this general formalism, the model of the Bouguer layer clearly shows that only water masses close to the gravimeter will have an influence, at least as long as $z_1 > Z_1$ and $z_2 < Z_2$ (these quantities being referenced to a local and plane level, with z-axis pointing down), because the attraction of such a layer is necessary smaller than the attraction of a layer with a maximum thickness of $Z_2 - Z_1$, which is equal to $2\pi G\rho_w(Z_2 - Z_1)$.

In a more general manner, the attraction of water masses can be estimated by direct numerical integration if the underground distribution is known but too complex to be approximated by elementary models.

The Bouguer sheet attraction corresponds to 41.9 μGal for each meter of water (no matter where located). However, referring to the variation of a piezometric level, one must take into account the effective porosity Φ that describes the effective volume of movable fluid into the porous medium. Hence, if Δh is the variation of a piezometric level, the induced variation of gravity, (assuming a water density close to 1) is $\Delta g = 2000\pi G\Phi\Delta h$ as expressed in the International System. For most aquifers, porosity varies from a few percent to 30%, at least as far as superficial geology is concerned. Taking as a typical example a 10% porosity (assuming Φ = 0.1), the variation Δh of a piezometric level (in m) induces a gravity variation of about $\Delta g = 4\Delta h$ (in μGal).

Nevertheless, we must not consider the piezometric level, this quantity being the most easily accessible in boreholes, because it is not fully representative of the entire water column. Also important is soil moisture, i.e. the water contained in the vadose zone that has not yet reached the free aquifer table or that has not disappeared by evapo-transpiration at the soil surface or through plants. Hence, a thorough evaluation of the phenomenon needs to consider all the water in transit from the surface to the water table, and to quantify that contained in the vadose zone, where capillary phenomena act.

2.2. Medium and large scales, L2

We consider now the computations related to water masses located at distances between L1 and L2 (medium or regional scale) or larger than L2 continental or global scale). The formalism commonly used in the study of ocean loading can be adapted here; it assumes a surface layer described with surface density values. Using this approach, the station location is supposed to be at the same altitude as this surface layer (or within it), and hence does not involve the attraction of local water masses that, in a more realistic model, are located above or below the gravimeter. As far as only water masses are concerned (neglecting redistribution processes), two attraction effects can be distinguished. One concerns the water masses directly beneath the gravimeter, that can be modelled by using a Bouguer infinite plate model (or refined Parker's model) as given above. As we have seen, the remote attraction contribution of such a layer can be neglected, while the remote loading effect (flexure and mass redistribution) of such a horizontal layer is unrealistic and has to be replaced by a formalism including the Earth's surface curvature. This second and new part becomes significant when the distance to the station is large (much more than 1 or 10 km). Let us now estimate the magnitude of this remote contribution as a function of the scale.

To manage with these "regional" (L1–L2) and global (>L2) scales, we make use of the classical loading formalism, as usually done in ocean loading computations. It takes into account the direct Newtonian attraction, depending on the curvature of the Earth – which puts water masses greatly beneath the instrument – the free air effect caused by the flexure of the crust and mantle, and finally the effect of masses redistribution associated to the deformation generated by this load. The recent results obtained for the oceanic loading problem and for the various stations of GGP show a good agreement between the computed results and the gravimetric observations (Baker and Bos, 2003; Boy et al., 2003). The discrepancy seems to be linked with errors in the oceanic models themselves, because the rheology of the crust is expected to have only a very slight influence.

The contributions of remote water masses can be computed by using two different ways: either in the spectral domain, by using spherical harmonic functions (Wahr et al., 1998) as for global Earth dynamics, or choosing a convolution formalism which uses a Green's function (see Farrell, 1972). The latter is the method of choice for the computation with loads of limited extension (e.g. Van Dam et al., 2001a,b); this approach is therefore more practical for the hydrological loading. Green's functions for radial displacement and gravity effect are:

$$u(\alpha) = \frac{a}{m_e} \sum_{n=0}^{\infty} h'_n P_n(\cos\alpha) \qquad \gamma(\alpha) = \frac{g}{m_e} \sum_{n=0}^{\infty} (n + 2h'_n - (n+1)k'_n) P_n(\cos\alpha) \tag{3}$$

where α is the angular distance between the load and the instrumental station, "a" the radius of the Earth, m_e its mass, g the mean gravity at the surface and P_n the Legendre polynomials of degree n. h'_n and k'_n are load Love numbers of degree n, computed by the integration of the equations of elasto-gravitation (e.g. Alterman et al., 1959; Pagiatakis, 1990); these numbers are computed for a stratified Earth model such as PREM (Dziewonski and Anderson, 1981).

Using the functions in Eq. (3) (that do not include the local attraction term, but both flexure and redistribution effects), the hydrological loading is easy to compute with a convolution algorithm. This leads to an estimate of either the induced gravity variation, or the radial displacement—which of course contributes to the variation of gravity, but which is accessible separately by precise positioning techniques such as GPS, VLBI or SLR.

More precisely, these two quantities are given by:

$$\Im(\theta, \lambda) = \rho_{\mathrm{w}} \iint_{\Omega} GF(\alpha) \times H(\theta', \lambda')\,\mathrm{d}S' \tag{4}$$

where θ and λ are the coordinates of the station, ρ_{w} is the water density, GF(α) is the Green's function of interest, and $H(\theta', \lambda')$ represents the height of the applied load on the elementary surface element dS', at location θ', λ'.

To estimate the magnitude of these terms, one uses a load defined by a centred homogeneous shell of water (of angular radius α), normalised thickness 1 m, and computes the induced effects as a function of angle alpha, that finally leads us to propose values and meanings for the distance L2.

Fig. 1 shows the behaviour of these loading effects versus the radius of the shell. The gravity effect increases monotonically with angular distance, from 0 to 65 μGal (Fig. 1a). On the other hand, one can observe a change in the sign of the slope of the vertical displacement (Fig. 1b). From 45°, a larger shell will diminish the loading effect on the terrestrial crust, up to about 110°, after which the displacement increases to final value of about 70 mm. Such a global homogeneous shell is, however, only useful at continental scales (for a low degree, 5–10, spherical harmonic expansion). This is as far as the seasonal rainfall and climate forcing permit us to match a model to realistic field conditions (beyond the distance on which the water levels are no longer correlated in space, the meaning of this estimation drops) (see Milly and Shmakin, 2002a,b).

Another way to schematically represent the consequences of continental hydrology is shown in Fig. 2a for gravity and Fig. 2b for the radial displacement. Again we assume a uniform water layer of 1 m thickness present all over Europe (see the white box for the limits) and the loading effects are computed using the Green's functions described above.

Let us now divide these magnitudes by a factor of 10, corresponding to a variation of groundwater level in an environment with a mean porosity of 10%. We then claim that gravity variations >1 μGal, and radial displacements >1 mm, begin to be sensitive beyond a size of the source shell which is found to be (see the small boxes in Fig. 1) 600 km for the gravity effect and 120 km for the radial displacement. At this threshold, (here 1 μGal and 1 mm), these two distances define the limits of L2 (one for gravity and one for vertical displacement). Below this threshold, the gravity or displacement effects due to the load of regional water storage can be neglected. This result is also of great interest for satellite applications because since the smaller gravity length scales are not reachable by satellites (see Kaula, 1966; Wahr et al., 1998). Our estimation leads to the unavoidable conclusion that the knowledge required to cross-validate space and ground-based data concerns either the strictly local groundwater content or the global hydrological storage. This permits us to propose three scales that depend on the threshold defined previously, as summarized in Table 1.

Now, let us consider the question of how to compare local gravity measurements to satellite data. Note that the gravity as seen from space or any other global approach involves a local term that is a smoothed by the fact it is remotely measured. The viewpoint from a ground station is different, because the local term is studied locally and is not affected by how representative a particular interpolation process may

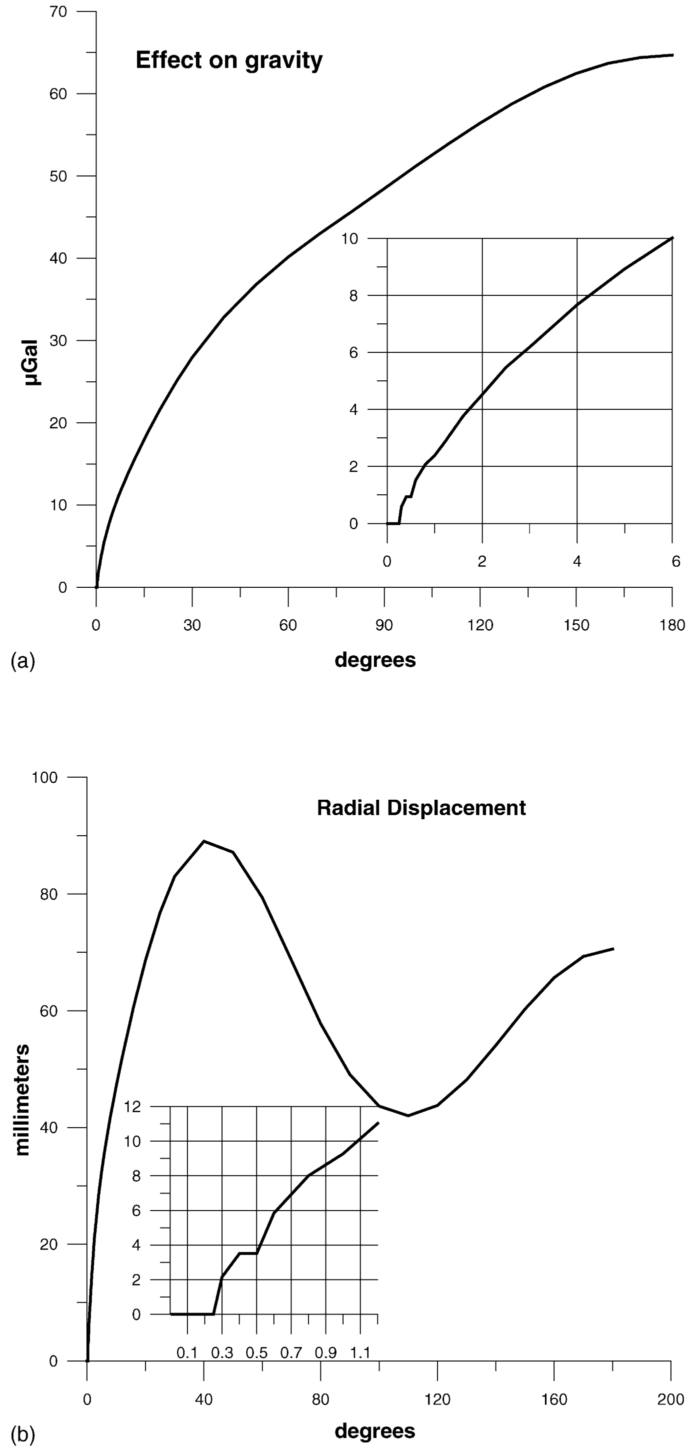

Fig. 1. Computation of the effect on gravity (a) and on the radial displacement (b) due to a uniform 1 m thick shell of water, as a function of the radius.

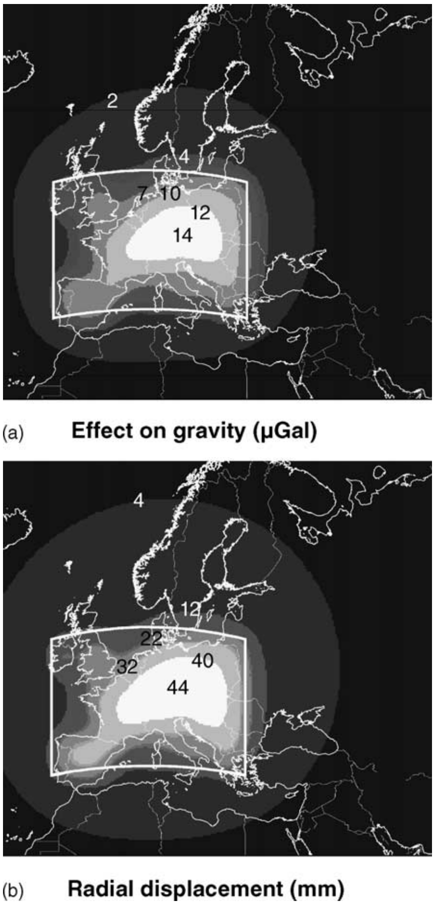

Fig. 2. Gravity change (in μGal) (a) and radial displacement (in mm) (b) caused by an hypothetical water table of continental size (the white box) in Europe of 1 m thickness.

be. One can compare this to the difficulty of interpolating a rapidly varying function from its smoothed form.

A possible scheme to compare gravity space data to ground-based data, based on signals originating from hydrology, could be similar to the following:

(1) take the global or smoothed water storage data as derived from space techniques (above Kaula's limit), and re-estimating (by convolution) the gravity contribution of water masses variations but putting a "hole" at the station location to cancel the local contribution seen from space. Let "*S*" be this quantity,
(2) estimate, by using station gauges (piezometers, soil moisture probes, evapo-transpiration models. . .) the total amount of underground water, and calculate the corresponding local gravity contribution, say "GW",
(3) add together S + GW, and compare to gravity residuals (gravity observations corrected for the usual known signals such as solid and ocean tides, atmospheric pressure, pole motion and instrumental drift) as given by superconducting or absolute gravimeters.

Table 1
Effects on gravity and vertical displacement due to hydrology for several distances around a given station

Distance effect	D < L1	L1 < D < L2	D > L2
Gravity variation due to Newtonian attraction of local water masses (within an horizontal plate)	Possibly significant, requires geological local studies and local environmental gauges (rain, soil moisture, ...)	Negligible	Negligible, L2 = 600 km to reach 1 μGal by using a 1 m layer and porosity = 10%
Gravity variation due to global attraction, flexure and mass redistribution	Negligible	Negligible	Significant and observable by using global environmental models. Can be computed by using a convolution formalism
Vertical displacement	Negligible	Negligible	Significant and observable, can be computed by using a convolution formalism. L2 = 120 km to reach 1 mm by using a 1 meter layer and porosity = 10%

Another very important point concerns the possibility of improving the use of temporal variations of gravity for the various applications as described by Crossley et al. (1999). For any application such as the search for core modes or tectonic purpose, one has to estimate as accurately as possible the ground water contributions in order to remove them from the observed signals. The study above shows that only the strictly local contribution (<L1) and the global one (>L2) need be carefully estimated, and that the regional water content, between L1 and L2, can be largely ignored. Because most remote contributions tend to be smoothed out by the implicit integration they involve, the hope of greatly improving the signal/noise ratio by retrieving the local water influences (that is easier to study by local probes and accessibility conditions) appears realistic. It necessitates the deployment of a cluster of environmental probes surrounding the station. The next part is devoted to the study of the hydrogeological context of several GGP stations in Europe in order to illustrate the variety of different situations, and how difficult it can be to characterise and estimate the local gravity contribution.

3. Three examples of hydrogeological environments

Several GGP stations have been investigated in term of hydrogeology contribution to gravity, and the impact of environmental forcing has often been addressed (see e.g. Harnisch and Harnisch, 1999, 2002; Virtanen, 2001; Ijpelaar et al., 2002; Jentzsch and Kroner, 1999; Neumeyer et al., 1999; Takemoto et al., 2002).

For the station Medicina in the Po valley, Zerbini et al. (2001, 2002) and Romagnoli et al. (2003) exemplified the benefits of recording auxiliary signals such as rainfall, water table level, soil moisture and other variables in understanding seasonal gravity changes. Here we present the hydrogeological context of three GGP stations in Europe: Strasbourg (France), Moxa (Germany) and Vienna (Austria). Fig. 3 shows the geographic location of these stations in Europe with a black circle of 600 km radius (L2 limit) around each.

3.1. The J9/Strasbourg station (France)

At the J9 station in the vicinity of Strasbourg, where the SG C026 is operating, cryogenic gravity data are recorded inside an old bunker on top of which a GPS antenna is also installed. Regular absolute gravity

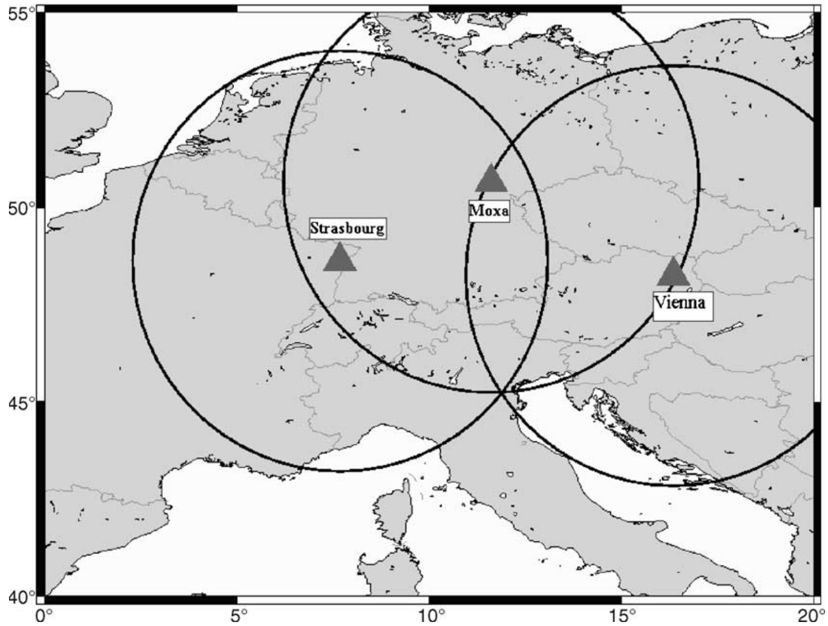

Fig. 3. Location of the three gravimetric stations considered in this paper. A circle of 600 km (corresponding to the L2 limit) is drawn around each station.

measurements are also available (Amalvict et al., 2004, this issue). The building is sited above the main Rhine aquifer, but close to its limit at the Eastern part of the Rhine graben (Fig. 4). Several kilometre to the East, the water table variations reach roughly 1 m, while inter-annual maximum changes can reach 2 m.

The bunker is built on a hill made of loess that hides the underlying layers. The hill represents the topographic response of a small local fault horst system at the border of the main graben, on which the wind sediments were trapped. Borehole measurements suggest the geological interpretative section shown on Fig. 5. From top to bottom, we successively find:

- a surface loess layer with a 25 m thickness, that damps underground water transit;
- a sand layer which holds the local aquifer;
- a clay layer of which the Eastern end is unreliable.

The loess layer is made of unstratified and unconsolidated sediments having a high porosity, but only semi-permeable properties. About 170–200 mm of water can be sustained by 1 m of soil, and partially evaporate or transit down to the free aquifer system. The amount of sustained water is maximum between November and February and minimum during summer. According to local hydrologists, the amount of water that effectively transits to the aquifer is estimated to be about 200 mm/year. Fig. 6 shows the monthly mean model of rainfall and evapo-transpiration deduced from a hydrology investigation on data recorded at the Strasbourg airport in the immediate vicinity (10 km) of our gravimetric station. Fig. 7 shows the corresponding mean changes in water content of the loess sedimentary layers; there is a clear annual signal with maximum thickness in winter and minimum in summer.

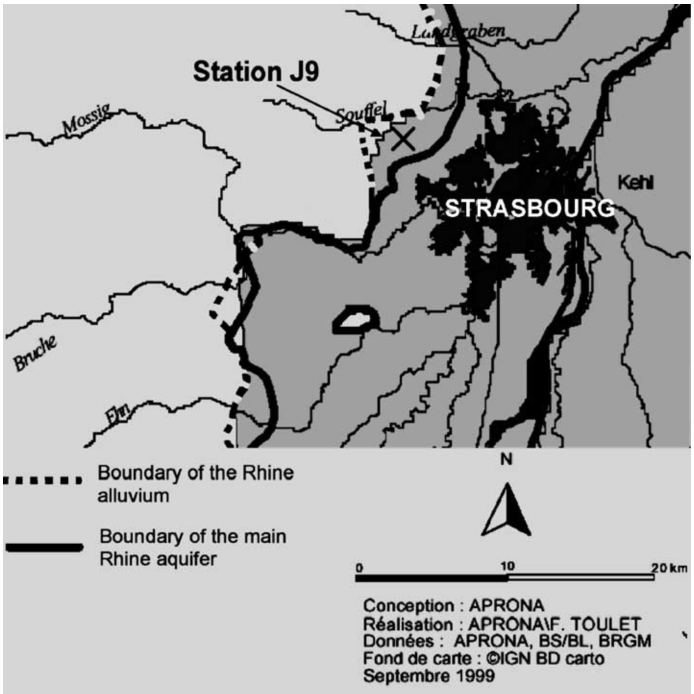

Fig. 4. Delimitation of the water table of the Rhine alluvium, in the vicinity of the J9 gravimetric station, North–West of Strasbourg (France).

A piezometer sited in a well within the bunker continuously records the local water table level (Fig. 8) within the sandy layer. Due to the topography, the water surface lies above the Rhine aquifer, runs independently of it and discharges at the hillside. The level range is found to be clearly compatible with the estimation above. Due to the lack of soil moisture data, we estimate the amount of gravity changes that results from the ground water content by using simple models or by studying correlations between gravity and water table levels.

The observed gravity variations show a good correlation with the water table level variations, and leads to an approximate linear dependence of 20 μGal m^{-1}, an with an uncertainty of 4 μGal between maximum and minimum values. This corresponds to a porosity of 40%, which is probably an overestimate. This can be due to the fact that local variations and continental ones are correlated through seasonal coherent variations: both crustal flexure and local water attraction act in the same direction, increasing gravity when the water level increases. Fig. 9b (thick line) shows the gravity prediction due to the local water table using this admittance value.

As noted above, to estimate the soil moisture contribution in the lack of any data is not straightforward. Another difficulty arises from the complex topography and background just around the gravimeter. Fig. 9a shows a simple model used for the computation of the gravity attraction due to soil moisture; the upper part is a section view indicating the 10 m deep location of the gravimeter below the surrounding top soil layers and the bottom part gives the geometry of the model. To first order, the equivalent water layer simulating the soil moisture trapped in the surficial loess terrains is modelled by two half cylinders (one

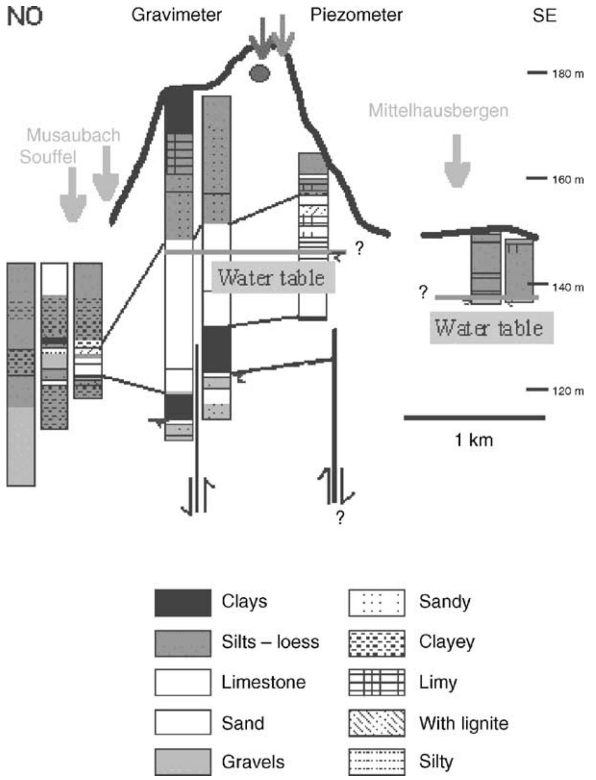

Fig. 5. Geological section of the Hausbergen hill (around J9 gravimetric station).

at a mean height of 190 m to the East, the other at 185 m to the West) of internal radius 30 m and extending to infinity.

Using this model to compute the attraction due to soil moisture leads to a value of about 1.5 μGal peak to peak for this contribution (see dotted line in Fig. 9b). Finally, the sum of these two terms is superimposed to the observed gravity residuals on Fig. 9c. Even if the curve agreement is not perfect,

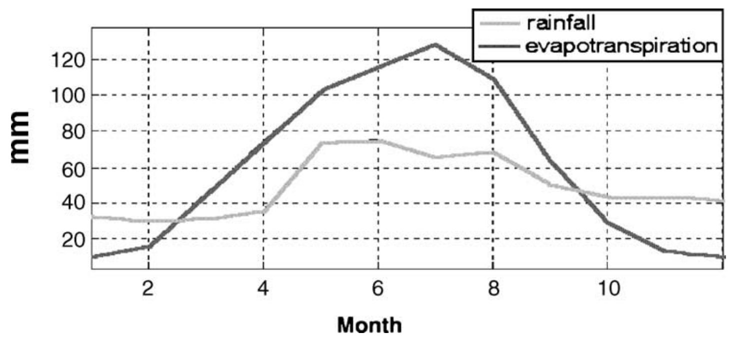

Fig. 6. Monthly mean model for rainfall and evapo-transpiration in Strasbourg (Entzheim airport values).

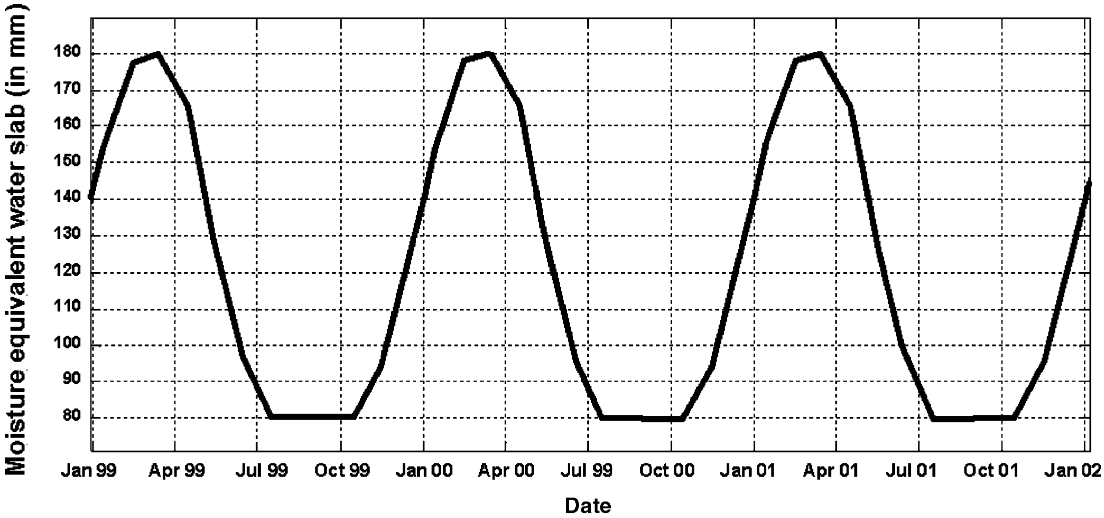

Fig. 7. Mean annual changes in water content in the loess sediments in Strasbourg.

it shows that the magnitude of the observed residuals can be easily reached by the local hydrological contributions.

We also considered other contributions, one from the main Rhine aquifer beyond the hill and the other from an important water storage tank, 1 km away from the station. Both effects were found to be negligible in practice (at least as far as we only consider contributions greater than 0.5 μGal), and this is in agreement with the consideration about the zone between L1 and L2 distances.

3.2. The Moxa station (Germany)

The geodynamic observatory Moxa was built about 30 km to the South of Jena in Germany (Fig. 10); the instruments are set up within a mine-like gallery (Jahr et al., 2001). The front part in which the SG is installed is covered by remains of the drilling of the gallery and by a soil layer of a thickness 2–3 m.

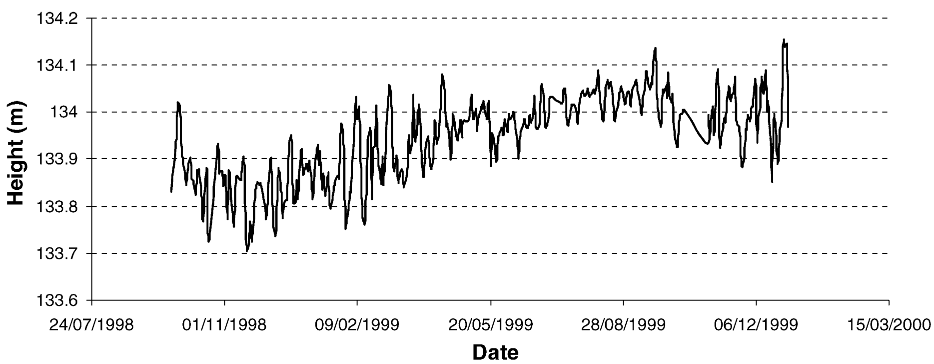

Fig. 8. Piezometric variations of the local water table measured in a well below J9 gravimetric station near Strasbourg.

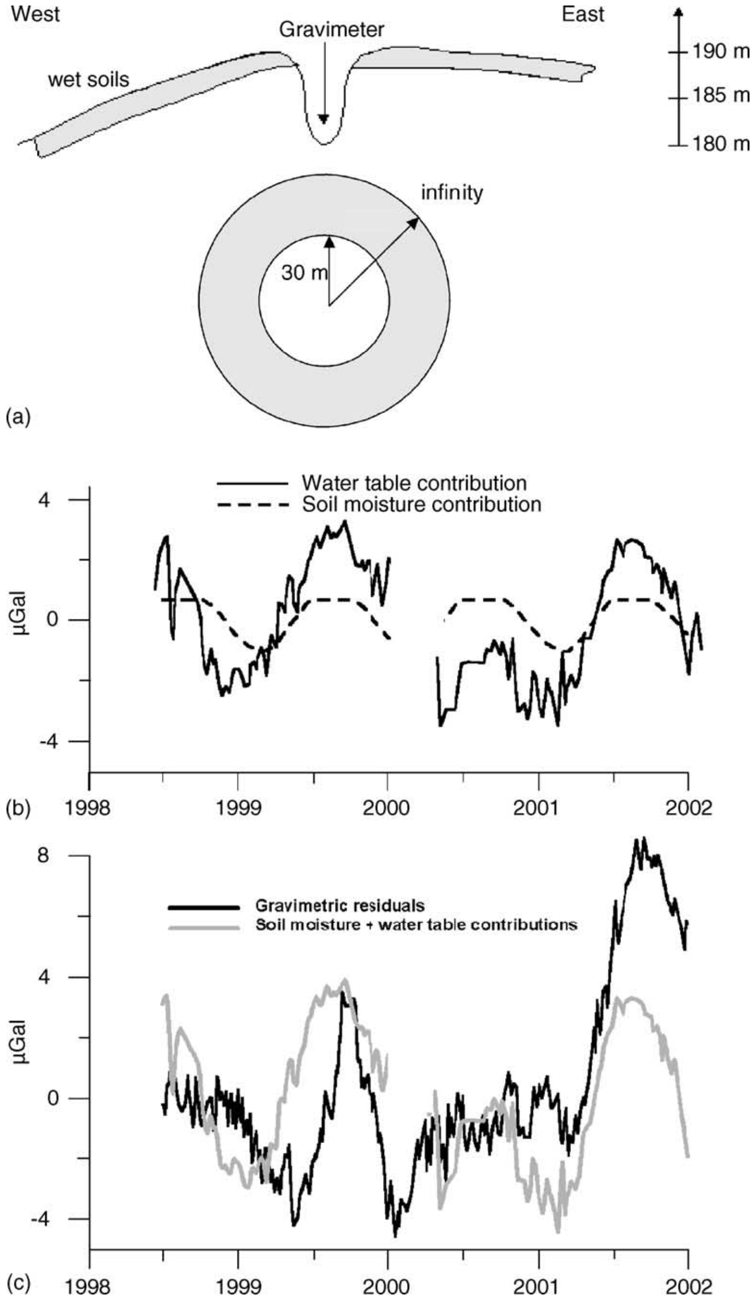

Fig. 9. Local hydrology contributions to gravity variations recorded at J9 station.; (a) is the elementary model used to estimate the gravity effect of soil moisture in the vicinity of the gravimeter; (b) shows the estimated contributions from the local water table and soil moisture changes assuming this elementary model; (c) superimposes the sum of these two contributions to the gravity residuals.

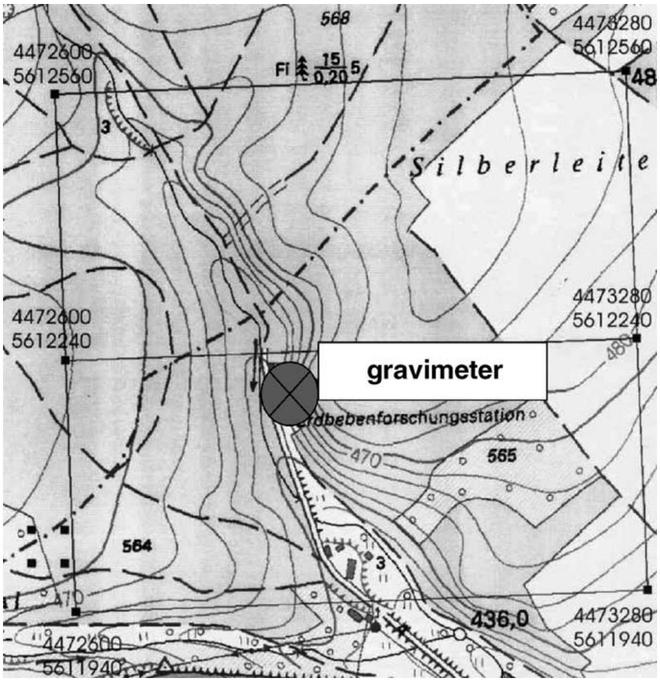

Fig. 10. Topographic map in the vicinity of the Moxa (Germany) station.

This station is also equipped with rain and water table gauges (50 m deep), and classical meteorological probes (Fig. 11).

As shown by Kroner (2001, 2002), significant hydrological effects in gravity occur at Moxa making a detailed analysis necessary. Most of the rainfall drains into a local stream, but the surrounding forest is very humid and the soil and the weathering layer can probably retain a significant amount of water. A sprinkling test has been done to estimate the possible signal due to water within the roof area that consists of drilling rubble (Kroner, 2001, 2002). This experiment sprayed onto the roof of the building a total amount of water equivalent to a 4 cm thick layer that run-off more or less quickly (Fig. 12). It induced a 1.2 μGal gravity signal (a corresponding admittance can be estimated as 30 μGal m^{-1} compared to 42 μGal m^{-1} that is the standard Bouguer value. Because the instrument involves two spheres in levitation, a differential signal has also been observed, as expected, and reaches 0.05 μGal that seems to be in agreement with a cylinder model of stored water on the roof of the station.

This experiment shows that at least the material over the roof behaves as *one* possible source of rainfall water storage. It also permits us to estimate the characteristic time of residence of the water on the roof that is very useful to convert rainfall quantities into gravimetric signal including the final leakage to the stream (although it relies on a strong simplification of the local topology). It is possible to model this system by considering a “roof reservoir” of surface (A) (that is instantaneously filled) where the water leaks through a permeable medium of surface (a), thickness (L) and permeability (K) (see Fig. 13). The conservation law plus Darcy’s law leads to a solution $h(t) = h_0 e^{-c(t-t_0)}$, where $c = AK/aL$ (and t_0 is the initial time of filling). Although rainfall immediately succeeded the experiment, it was possible to obtain a first insight to parameters $c = 6.5 \times 10^{-4}$ s^{-1} (time constant = 2 h and 30 min) and $K = 10^{-2}$ m s^{-1} that

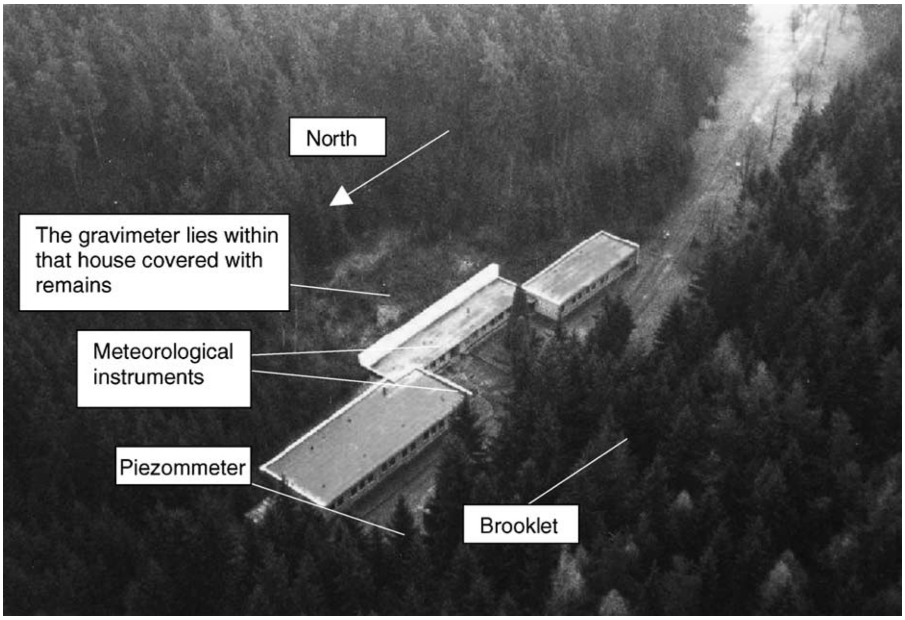

Fig. 11. A view of the Moxa geophysical observatory.

are in agreement with the nature of the roof material. Hence, the induced gravity signal can be written $g(t) = \Gamma \int h_0(\tau)\,\mathrm{e}^{-c(t-\tau)}\,\mathrm{d}\tau$, with $h_0(\tau)$ is the water amount fallen at the time τ, and Γ the previous admittance (c.f. Crossley et al., 1998 for a simpler analysis of the same problem).

However, it appears that these short term "roof" variations do not represent the full water rainfall influence. Indeed, the station is sited in a small valley bottom, in that way that surrounding soil layers are about 35 m above the gravimeter (at the East). A first raw estimation (a semi-plate at the mean location of the hill top) leads to an admittance contribution of 10 μGal m^{-1}. This value is, however, much too big. A more sophisticated estimate was done (Kroner, 2001, 2002) by digitising the area and calculating the

Fig. 12. Sprinkling test at the Moxa observatory.

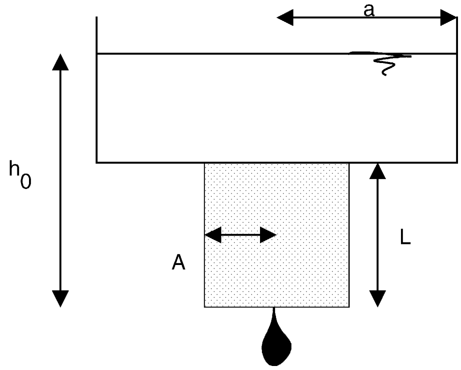

Fig. 13. Schematic description of a model of water discharge in schist debris; (A) is the “roof reservoir” (that is instantaneously filled) where the water leaks through a permeable medium of surface (*a*), thickness (*L*) and permeability (*K*).

gravity effect of the rectangular areas. An estimation of the effect of about 2 μGal m^{-1} for each hillside assuming a change in water filled pore volume of 10% was obtained. In addition it would need to take into account the changes below the gravimeter horizon.

When observing the ground water level record versus that of gravity, from 28/04/2000 to 05/05/2000, it becomes clear that these two signals are anti-correlated (Kroner, 2001, 2002), so the groundwater recharge (of the near-surface layer) coincides with a decrease of the gravity signal. Although the admittance changes from one event to the following (and the water level probe is only representative of the valley bottom), it is fully compatible with the value estimated above, between 5 and 15 μGal m^{-1}.

3.3. The Vienna station (Austria)

The Austrian superconducting gravimeter which is supported by the Institute for Meteorology and Geophysics lies in the centre of the city of Vienna, on the hillside just above the Danube River. Rainfall and soil moisture data are monitored in the park close to the gravity station (Fig. 14). The geological context consists in basin that evolved from the beginning of Miocene, as a pull-apart feature involving several sedimentary episodes, until the end of Pliocene. It ended by an inversion of the tectonic conditions that raised the Danube basin (Decker, 1996). The various tertiary deposits show high lateral variability. The inner geomorphology is complex and consists of several local aquifers that are hard to distinguish and characterise. Because most of the sediments are consolidated, the mean vertical permeability is low, while the Danube recent sediment dynamical porosity reaches about 10%. Fig. 15 summarises the geological section. Although the sandy soil around the instrument can accommodate a free aquifer of significant size, the deeper groundwater could be confined.

Sudden summer thunderstorm rainfalls form the main meteorological water contribution. An increase can also be observed in November, while the evapo-transpiration is minimum. Because the gravimeter area is horizontal and flat, rather high frequency gravity variations are expected. Since 1996, the city of Vienna has managed a protective policy to prevent flooding, and the banks of the Danube have been reinforced. A system of hydraulic pump stabilises the piezometric levels over a large extent of the West Danube aquifer.

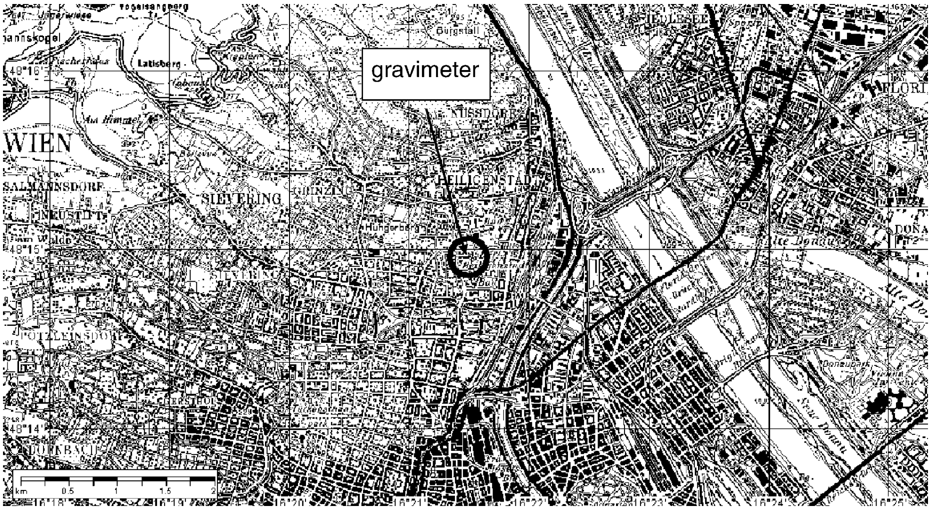

Fig. 14. Map of Vienna (Austria) showing the location of the superconducting gravimeter.

After correction for the usual known signals (solid and ocean tides, atmospheric pressure, pole motion and instrumental drift) and low-pass filtering the residuals at 10 days, the long-time gravity residuals exhibit a seasonal feature which decreases since 1999 (Fig. 16). By comparison, when considering short period records, one observes a remarkable correspondence between big rainfalls and gravity changes in which the gravity variations occur before the rainfall itself. Meurers (2000, 2001) has interpreted this as a redistribution of atmospheric masses (vertical density changes due to water condensation) during storms, without pressure change. A few hours after the stormy event, air masses stabilise and the gravity recovers its initial level.

The atmospheric and hydrological contributions are difficult to differentiate during such events, and it is not easy to determine whether a theoretical groundwater admittance value of $-12\,\mu\mathrm{Gal\,m^{-1}}$, as derived from a elementary geometric calculation, could be applied. Assuming that the main part of the summer rainfall evaporates quickly, and that the slow increase in gravity after the storm is due only to

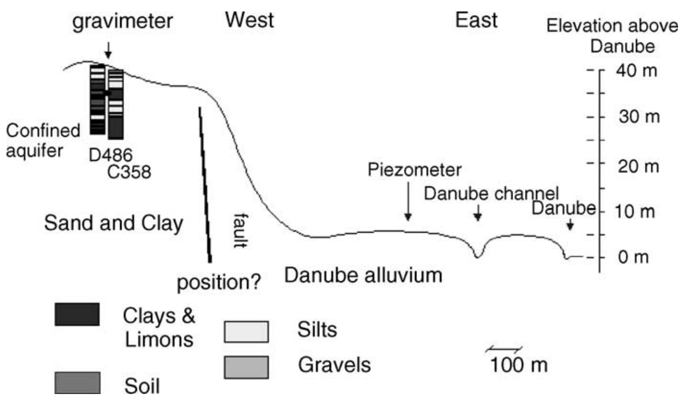

Fig. 15. Geological section of the Danube hillside in the vicinity of the gravimeter.

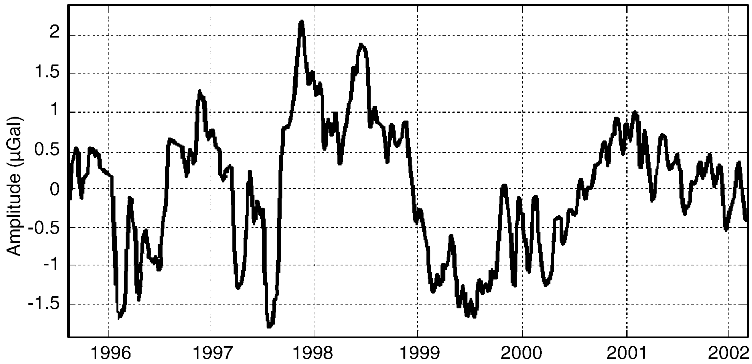

Fig. 16. Low frequency gravity residuals observed in Vienna, after correction for tides, atmospheric pressure, pole motion and some instrumental drift, and applying a 10 day low-pass filter.

the decrease of the air density anomalies and to groundwater evapo-transpiration, an exponential fit of the form $\Delta g = a\mathrm{e}^{-b(t-t_0)}$ leads to a change of $-0.45\,\mu$Gal during 14 mm of rainfall. At the same time, the atmospheric pressure influence is close to $-0.3\,\mu\mathrm{Gal\,hPa}^{-1}$ (here it is the dominant phenomenon), and hence the pure hydrological signal would correspond to the difference $-0.15\,\mu$Gal, leading to a hydrological admittance of $-11\,\mu\mathrm{Gal\,m}^{-1}$ that seems in agreement with the predicted one. This case illustrates once more the difficulties that arise in separating different environmental factors that play a role during a meteorological event.

Danube's alluvium water table contribution has also to be quantified. A simple modelling permits to evaluate the admittance with respect to this aquifer to be $2.0\,\mu\mathrm{Gal\,m}^{-1}$. Although a unique piezometer is not sufficient to fully describe the running of an aquifer, some events, like the rainy month of February 1996 are easily monitored by the gravimeter. This Vienna station illustrates well the difficult challenge in correcting gravity for various environmental effects. For this station the identification of an effect of atmospheric density variations without a corresponding surface pressure variation makes it very difficult to distinguish atmospheric from hydrological factors. Some contributions can act in opposite ways, depending on the location of the instrument with respect to the various water reservoirs. In the case of Vienna, the loading of the Alps snow should also be taken into account.

4. Conclusion

Underground water contributions must be taken into account while quantifying gravity variations at the μGal level or better. We have shown that hydrological contributions to gravity can be separated into three major scales—namely local, regional and continental sizes. The local scale (say less than 10 km) is dominated by the Bouguer attraction effect of the nearby water masses beneath the gravimeter and the effective porosity is a key factor. The computation of the elastic loading effects with the help of Green's functions has allowed us to propose specific distances which separate the regional from the global contributions. These specific distances are found to be around 600 km for gravity (at the μGal level) and 120 km for the radial displacement (at the mm level). We also addressed the point of the comparison of ground-based data to satellite data and proposed a scheme for such a comparison.

The second part of this paper was devoted to three case studies (Strasbourg, France; Moxa, Germany and Vienna, Austria) concerning the hydrological impact on gravity in Europe with the help of SGs and environmental data such as rainfall, evapo-transpiration, piezometric level and soil moisture models. In all three cases, even if the gravity residuals can be partly attributed to hydrology because of similarities in the observations and models, the problem has been shown to be difficult, due at least in part to the lack of the adequate environmental data.

Satellite missions dedicated to observing gravity will provide water content at a global scale with accuracy better than any ground hydrological dataset, but they will not provide suitable data at local scale. To build an integrated understanding of groundwater contributions to gravity at ground-based stations such as GGP, detailed hydrogeological studies must be undertaken and environmental parameters monitored with a suitable resolution, both in time and space. Although these problems may sometimes appear less attractive than some others, they generally require significant investment that is fully relevant to separate different gravity variations and finally analyse and understand them. A special attention must be paid to monitor the unsaturated zone. These tasks are especially necessary to clean the gravity signals from environmental forcing and must be considered in the retrieval of other, more subtle, signals. We are thinking here of those linked to possible core dynamics or other environmental signals of oceanic or atmospheric origin in a period range from a few minutes (during rainfalls) to secular scale including seasonal effects.

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