Long and short term hydrological effects on gravity in Vienna

Bruno Meurers[1)]

[1)] Institute of Meteorology and Geophysics, University of Vienna, UZA II, Althanstrasse 14, A–1090 Wien, Austria. bruno.meurers@univie.ac.at

Abstract

Some typical hydrological effects (precipitation, groundwater) observed in the gravity time series of the superconducting gravimeter (SG) Vienna are analyzed in detail. The contribution focuses on short-term meteorological events (heavy rain) associated with rapid gravity drops and on long-term hydrological loading effects. In contrast to precipitation data in high temporal resolution, unfortunately no groundwater table and soil moisture observations are available at the station. Groundwater table variations observed at distant wells are anti-correlated to the long term (seasonal) gravity signal although the aquifer is below the SG sensor. Newtonian water loading effects of different origin like rain, groundwater table fluctuations or snow cover are estimated using high resolution terrain models. The area in very close vicinity of the station (<100 m) turns out to play the dominating role. The gravitational effect of water level variations of the nearby Danube River is estimated to be less than 3 nms^{-2}.

Introduction

Geodynamical gravity signals are affected by surface mass variations due to atmospheric processes and redistribution of the atmosphere's water content by precipitation, evapotranspiration and water flow. Surface mass changes and associated elastic loading cause long-term but also short-term (< 1 h) gravity signals of several 10 nms^{-2}. In order to separate geodynamical signals it is necessary to understand the effect of these environmental processes. Recent studies (e.g. Kroner 2001, Harnisch and Harnisch, 2002, Boy and Hinderer 2006, Kroner and Jahr 2006, Van Camp et al. 2006) underline the importance of acquiring and evaluating additional environmental parameters like soil moisture, precipitation, groundwater and continental water storage. A ten years' time series of high resolution gravity and air pressure data is available obtained by the superconducting gravimeter (SG) GWR C025 which has been operating since August 1995 in the seismic laboratory of the Central Institute of Meteorology and Geodynamics (ZAMG) in Vienna (Austria). Investigating long-term gravity effects is difficult at this station because of two reasons:

- High station noise hampers sufficiently accurate instrumental drift determination by absolute gravimeter observations.
- No groundwater table or soil moisture sensor is available in close vicinity of the SG.

This paper tries to clarify which environmental signals can be expected in Vienna and estimates the effects taking the topographic conditions into account. Previous investigations have clearly demonstrated that in case of rainfall the area in close vicinity of the station plays the dominating role (Meurers 2000, Meurers et al. 2006).

Hydrological and topographic situation

The SG in Vienna is installed in the base floor of a large building. The underground consists of late Tertiary Vienna basin sediments. The uppermost soil is characterized by interbedded strata of sand, silt and gravel. Several drillings within the building area detected a water-bearing formation about 14 m below ground. A well exists close to the SG site for extracting industrial water. Its actual water table corresponds to the findings of the subsoil examination. The SG sensor is located about 8-9 m below ground i.e. rain and increasing soil moisture are expected to generate a gravity decrease while raising groundwater table should cause gravity increase. Water load modeling is very sensitive to the topography and to the local station geometry. It is important to consider impermeable areas like buildings or sealed surface from where water is drained immediately. Additionally, within the building area soil moisture does not contribute to gravity variations either (Fig. 1). The building is located on a gentle topography slope. The surface close to the station is well above the SG. However, this does not hold for the distant terrain. Therefore the gravity effect of mass distributed above and below the station partly compensates each other (Fig. 2).

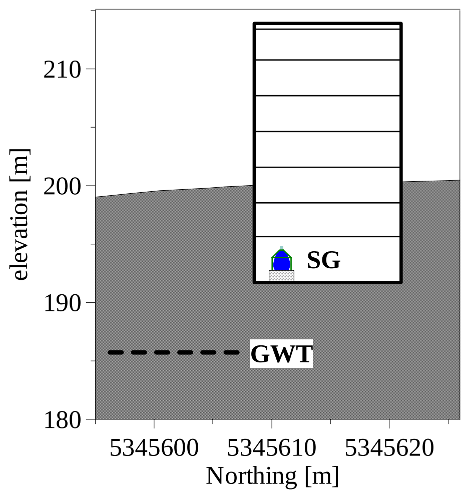


Fig. 1: Location of the SG sensor on the base floor of the ZAMG building, about 8 m below topography surface, GWT: Groundwater table.

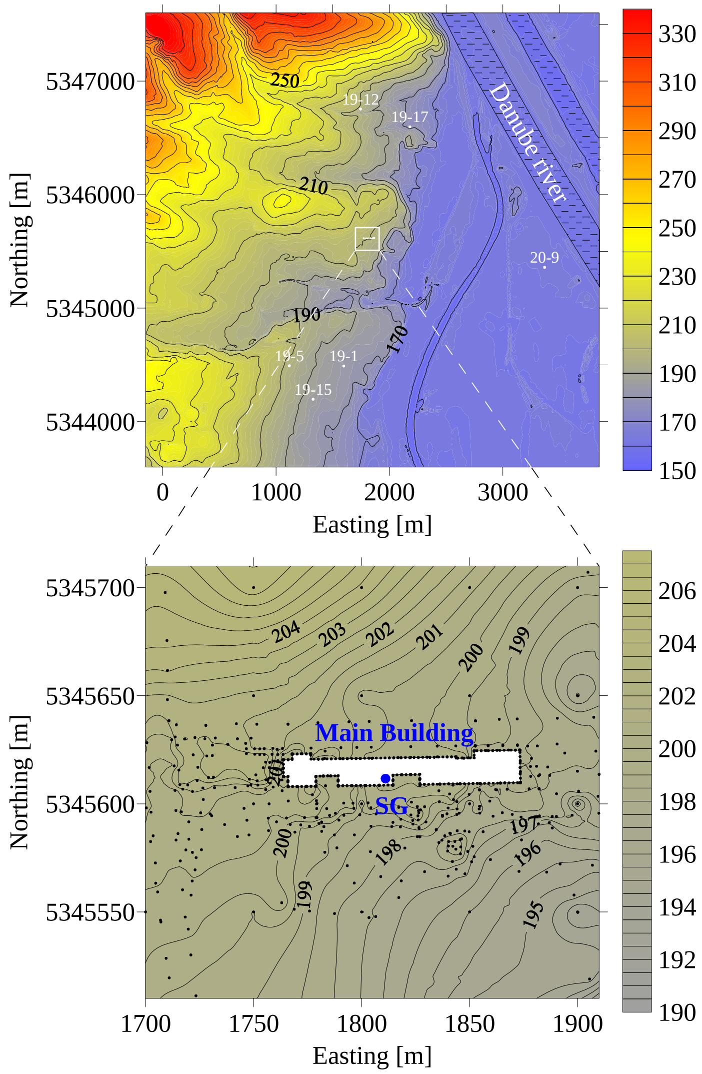


Fig. 2: Topography within the vicinity of the SG station. White dots indicate the location of selected groundwater measuring points from where groundwater table data is available. Note the different contour interval [m] in the lower panel where black dots represent the DTM data. The blanked area represents the building where no water is stored in the soil. SG sensor elevation: 192 m.

Long- and short-term rain effects

Precipitation data in high temporal resolution show that even small rain events are immediately imaged by corresponding gravity signals. The dominance of the local contribution permits to apply simple rainfall admittance in order to correct for the rain effect routinely (Meurers et al. 2006). Fig. 3 demonstrates that only the close vicinity contributes to the gravity effect due to the specific topography. The gravity drop during rain events can often be explained by the water mass load, but in numerous cases the Newtonian effect of vertical air mass redistribution (vertical density variation without air pressure change) plays also an essential role (Meurers 2000). Fig. 4 shows one typical example where the model reflects the cumulative rainfall effect correctly but indicates additional atmospheric effects at the beginning. In Vienna the model fits 50% of all rain events perfectly. However, even in most of the other cases the water load model is able to explain the dominating part of the residual drop especially when heavy rain fall is involved.

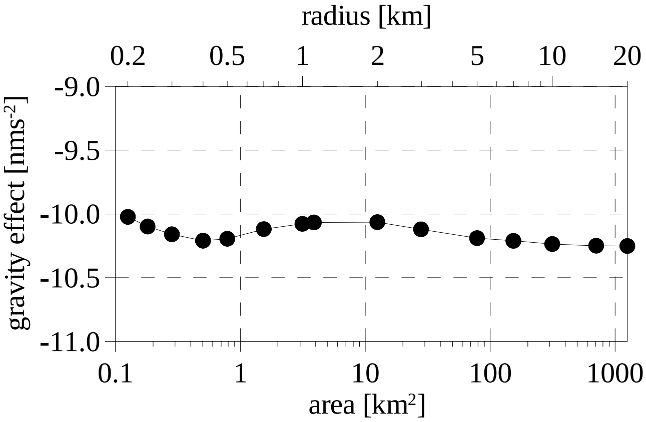


Fig. 3: Gravitational effect of a circular water layer (thickness 40 mm) spread on topography and centered at the SG sensor position for different radii. The gravity effect does not much vary with the extension of the contributing mass load due to compensation effects of distant layer parts.

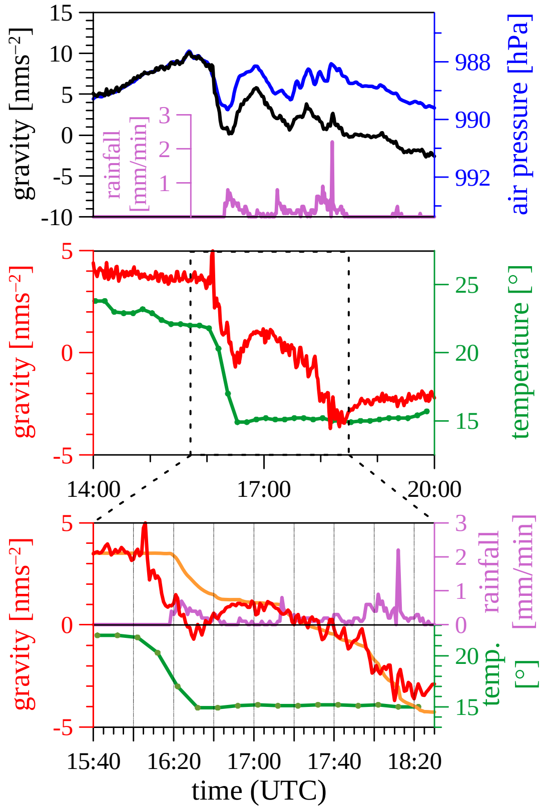


Fig. 4: Gravity variations caused by heavy rain and meteorological processes. Vienna, 2000 05 18.
Top: air pressure (blue), tide free gravity measurements (black) and rainfall samples (violet).
Middle: gravity (dark red) corrected for the air pressure effect [admittance factor: –3.53 nms^{-2}/hPa]. Air temperature (green).
Bottom: exaggerated section of the middle panel, water load effect (orange), 1 min rainfall samples (violet). The model reflects the cumulative rainfall effect correctly but indicates additional atmospheric effects at the beginning.

The rain admittance concept does not consider water flow due to run-off and evapotranspiration. Therefore rain water load *rwl* has been defined according to eq. (1) by considering a discharge process similar as proposed by Crossley et al. (1998):

$$(1)\quad rwl(t) = \sum_{j=-\infty}^{0} r(t + j\,\delta t)\frac{1}{2}\left(e^{j\delta t/\alpha} + e^{j\delta t/\beta}\right)$$

t is the time and δt = 1 min the sampling interval of the rainfall r. The discharge parameters α accounts for fast run-off after the rain fall event and β for much slower evapotranspiration.

They have to be tuned in such a way, that rain related gravity signals are minimized. Fig. 5 shows examples for three selected heavy rain events.

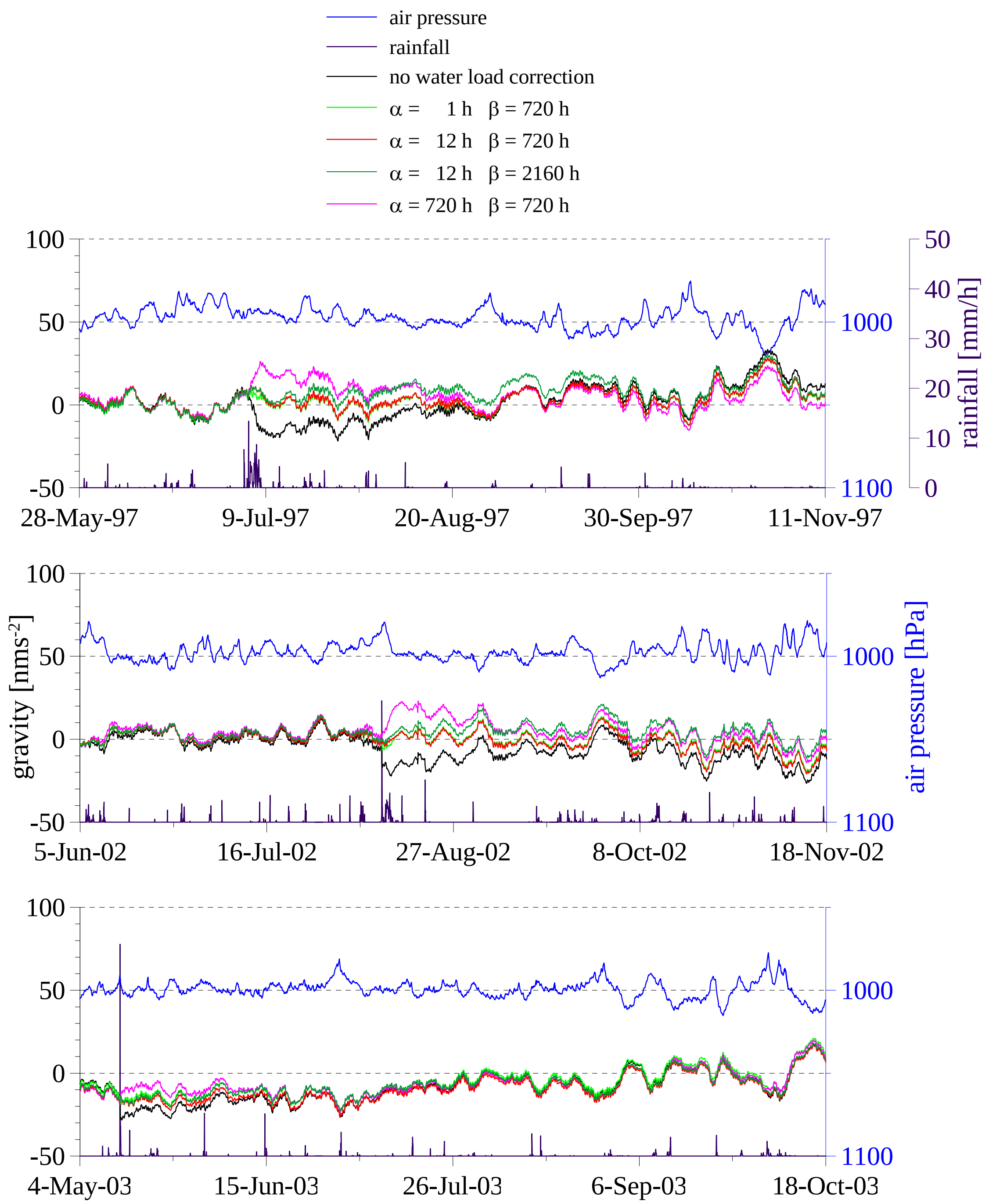


Fig. 5: Influence of the discharge parameters on gravity. Drift free gravity after subtracting the air pressure effect [admittance factor: –3.53 nms^{-2}/hPa] is displayed in black (no water load correction) or different colors (water load correction assuming different discharge parameters). Air pressure (blue) and hourly rainfall (violet) are shown additionally. The best result is obtained for α = 12 h and β = 720 h (red) or even much slower discharge (β = 2160 h, dark green).

There is a link between soil moisture and the slow discharge process. Rain water is the most important supplier for soil moisture. That part of rain, which does not run off at the surface or evaporate immediately, invades the soil from where it is removed later by water flow and evapotranspiration.

Groundwater table variations

No groundwater information is available at the SG site. However, several measuring points of the municipal office of hydraulic engineering can be used to investigate trends and seasonal variations. Groundwater data is sampled there once a week in average. The wells utilized in this study are marked in Fig. 2 (white dots) and Fig. 6 (colored dots). Because they are scattered over the entire area of Vienna they certainly do not represent a common aquifer. Besides, those stations located in the lowland near the Danube River (21-1, 22-212) are influenced by activities of the hydroelectric power plant South of Vienna. Others may be affected by industrial water extraction as well. Nevertheless, clear common seasonal features and trends are visible in the groundwater table data of all wells (Fig. 6).

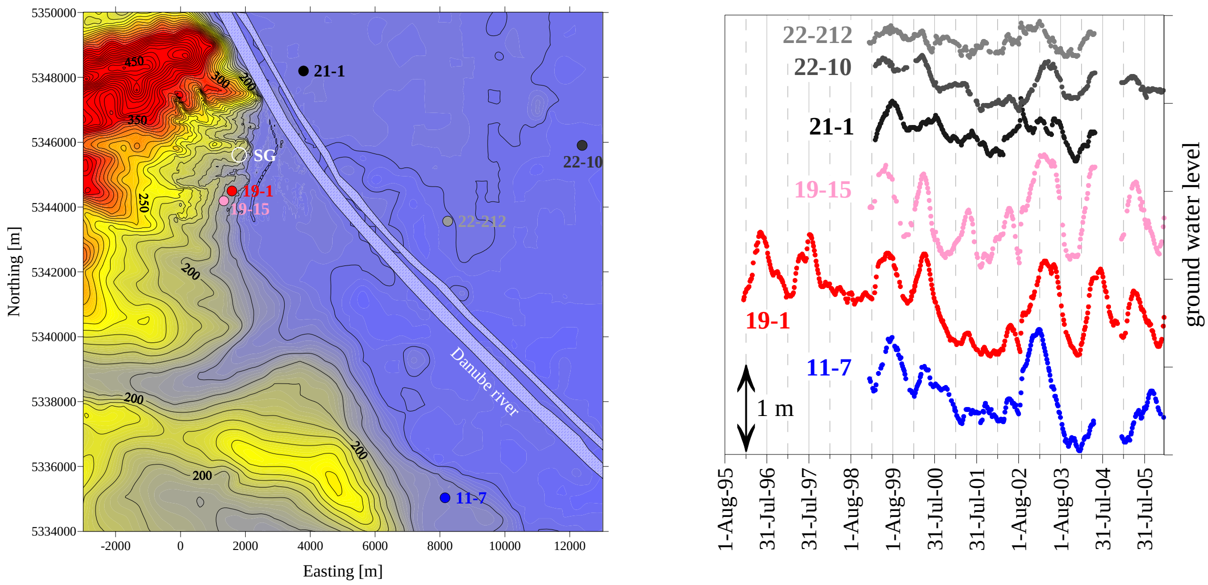


Fig. 6: Elevation map of Vienna (left) and groundwater table variations (right) observed at selected wells (marked as colored dots in the map).

Fig. 7 compares the drift-free gravity with the groundwater table data of well 19-1 that is located next to the SG (both smoothed by applying a running mean procedure).

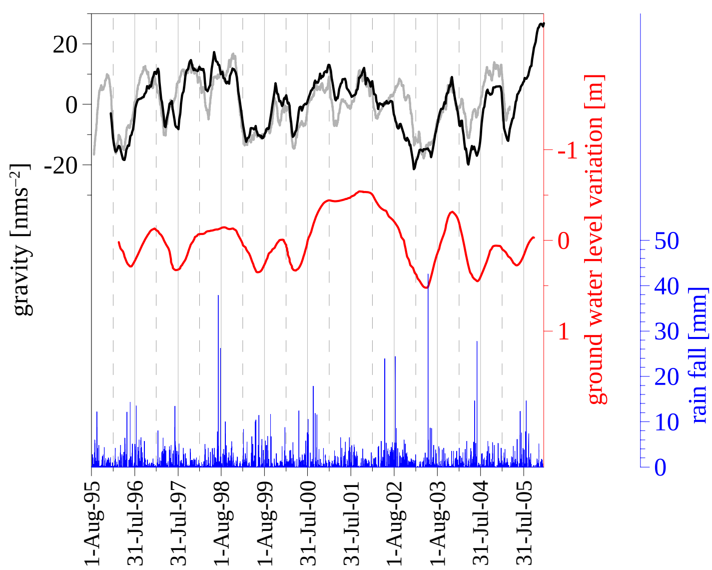


Fig. 7: Smoothed gravity (black) and groundwater table variations (red) at well 19-1. Rainfall is displayed in blue. The grey line indicates gravity after rain water load correction by applying the rain admittance and discharge model (α = 12 h, β = 2160 h)

Surprisingly gravity and groundwater table are anti-correlated although the SG sensor is located above the aquifer. There are different explanations:

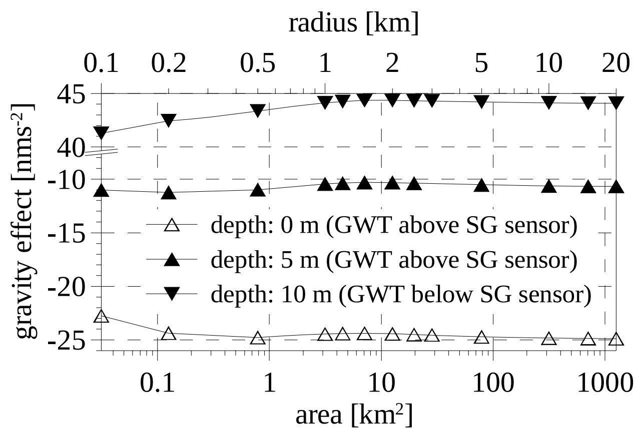
- Either there is no groundwater table variation at the SG site or the effect is overcompensated by soil moisture or other sources. However, applying the discharge model and different discharge parameters does not essentially change the seasonal gravity fluctuations. Contrarily, this correction seems to enhance the pattern of low gravity in late winter and high gravity in late summer or autumn (Fig. 7, grey line). This favors an alternate interpretation, that
- gravity reflects long-term effects caused by continental water storage (e.g. elastic deformation) that correlate with local groundwater table variations. Of course, this has still to be verified by calculating the load contributions.

In order to check the pure Newtonian effect of water load 3D modeling has been performed assuming the aquifer being located below and alternatively above the SG sensor in spite of the fact that the latter contradicts what we presently know about the groundwater table at the SG site.

A water layer of constant thickness (1 m, porosity of 10%) and at constant depth below the ground represents the aquifer. As in case of rain effect calculations, a polyhedral surface defined by Delaunay triangulation (e.g. Renka 1996) of the irregularly scattered terrain model data approximates the upper and lower layer boundary. The digital terrain model (DTM) consists of different data sets with distance dependent resolution. The average point interval varies from 10 m next to the SG to 20 km in far distant zones. By applying the method of Götze and Lahmeyer (1988) the corresponding gravity effect can be calculated precisely.

Fig. 8 shows again that the area more than a few 100 m apart from the sensor does not contribute significantly to the gravity effect in Vienna. If the aquifer is assumed to be located above the SG sensor the result depends strongly on the layer depth due to the missing contribution from inside the building. The extremum estimate is obtained when the depth to the aquifer vanishes (Fig. 8, open triangles). Even in this unrealistic case a much larger fluctuation than observed would be required to explain the seasonal gravity effect by groundwater table variation.

Fig. 8: Newtonian effect of a circular water layer (thickness 1 m, parallel to topography) representing the aquifer in a depth of 0 m, 5 m (aquifer above the SG sensor) and 10 m respectively (aquifer below the SG sensor) for different radii.



Groundwater table variations within the Vienna basin, the elevation of which is less than that of the SG sensor everywhere, have also been estimated. Assuming a porosity of 10% the gravity increases just by less than 2 nms^{-2} per groundwater table increase of 1 m. This is far below the amplitude of observed seasonal gravity fluctuations.

Newtonian gravity effect of snow cover

Snow generates gravity signals, which differ from those of rain, because

- snow does not invade the soil, and
- no run-off occurs at the surface

unless snowmelt starts. Possible seasonal effects have been estimated based on climatological findings (Fig. 9). At the same time this study also estimates the gravity effect of far distant (> 20 km) load of different origin. Between 100 m – 100 km remote from the station the Newtonian effect of surface water or snow is partly compensated (Fig. 10). Due to earth curvature this does no longer hold for distant areas where load always increases the observed gravity.

Fig. 9 demonstrates that far distant zones do not contribute significantly to gravity even in case of snow accumulation. Again, solely the very close vicinity is critical. Extending the snow cover area beyond a circle of about 100 m radius changes the gravity effect by less than 1-2 nms^{-2}.

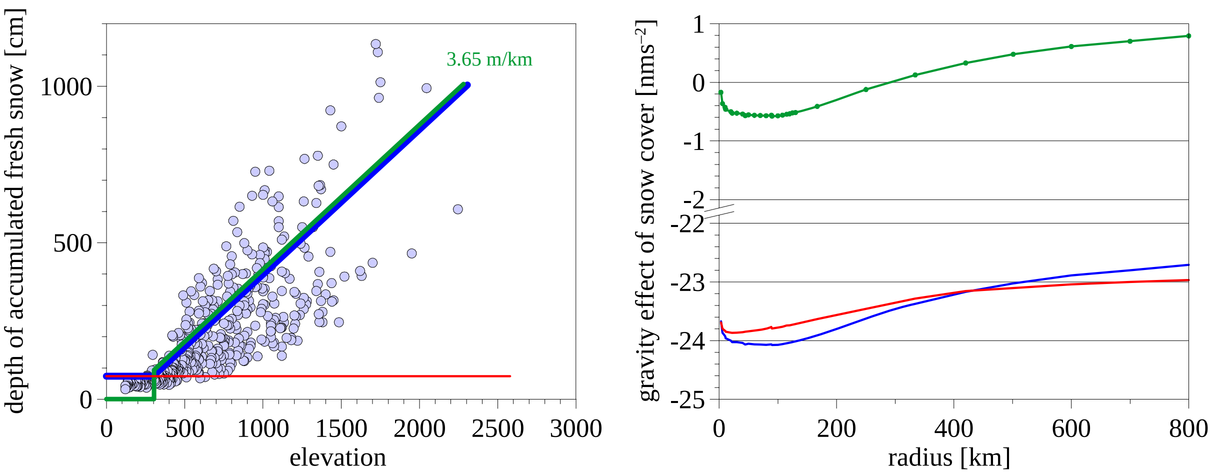


Fig. 9: Mean depth of accumulated fresh snow per year at climatological stations in Austria (light blue dots) and snow cover models (left); modeled gravity effect at the SG site in Vienna (right): height dependent snow depth (blue), height dependant snow depth but no snow cover below 300 m (green), constant snow depth of 0.745 m (red).

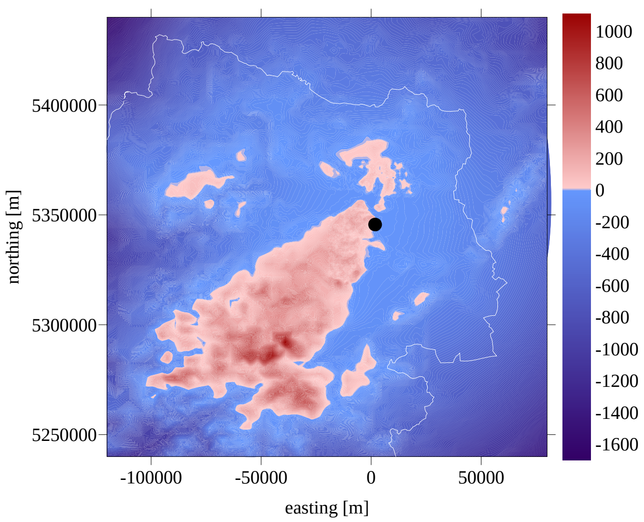


Fig. 10: Relative topography referred to the SG sensor in Vienna (black dot). Due to earth curvature the Newtonian effect of water load increases gravity at the SG site except of the close vicinity and those parts located in SW and S mainly.

Newtonian gravity effect of Danube River high water

The Danube River is located below the SG sensor. Water level actually varies by up to 5 m in case of high water (e.g. August 2002, Fig. 11). Within the Vienna area an artificial flood discharge streamlet has been constructed parallel to the river for flood regulation, which is opened occasionally. This reduces the water level increase of the main river to 2 m approximately while the water level of the channel varies between 5 m at the beginning and 2 m at the end. The corresponding gravity effect has been estimated as 0.65 nms^{-2}/m. Because high water is developing over a couple of days these small signals can not be separated.

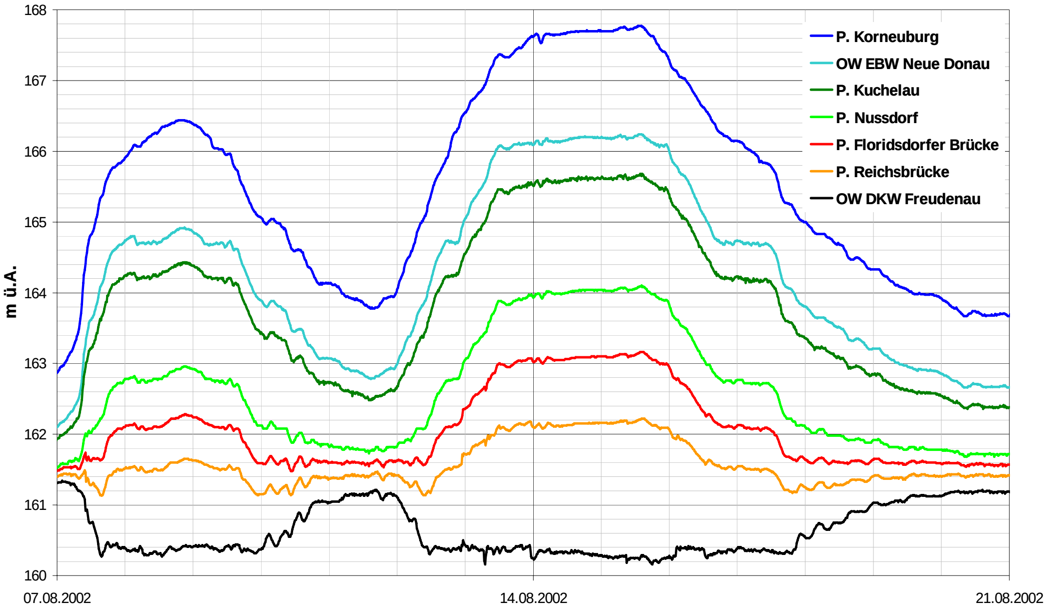


Fig. 11: Water level variations [m] of Danube River in the Vienna region for the flooding event of August 2002 (Gutknecht, 2004). The upper 3 lines represent the situation before flood regulation gets effective contrary to the lower 4 lines.

Conclusions

No groundwater data is available at the station itself, but it is known from drillings that the first water bearing stratum is located below the SG. Gravity and groundwater table variations as observed in wells about 1 km apart are anti-correlated. This indicates that the gravity effect of groundwater table variations either is small at the SG site or overcompensated by much stronger signals caused by soil moisture and/or other sources. Applying different discharge models does not essentially influence the long-term gravity fluctuations but enhances the typical pattern of low gravity in late winter and high gravity in autumn. It has still to be verified by analyzing large-scale load contributions if continental water storage signals (e.g. elastic deformation) causes the long-term gravity variations.

3D modeling of large-scale (ground-) water or snow load shows that the area in very close vicinity of the station (<100 m) turns out to play the most dominating role as long as the Newtonian effect is considered. Extending the load area beyond a circle of about 100 m radius up to a distance of 1000 km generates an additional gravity increase as small as 1-2 nms^{-2}. Water level variations of the nearby Danube River cause very low amplitude signals of less than 3 nms^{-2}.

References

Boy, J.P. and Hinderer, J. (2006): Study of the seasonal gravity signal in superconducting gravimeter data, J. Geodyn. 41, 227-233.

Crossley, D.J., Xu, S. and van Dam, T. (1998): Comprehensive analysis of 2 years of SG data from Table Mountain, Colorado. In: Proceedings of the 13th International Symposium on Earth Tides, Brussels, July 1997. Obs. Royal Belgique, Brussels, 659–668.

Götze, H.J. and Lahmeyer, B. (1988): Application of three dimensional interactive modeling in gravity and magnetics, Geophysics, 53, 1096-1108.

Gutknecht, D. (2004): Abflussbildung bei Hochwasser. Symposium FLOOD RISK Analysis of the Floods of August 2002, 24./25. November 2004, Vienna.

Harnisch, M., Harnisch, G. (2002): Seasonal variations of hydrological influences on gravity measurements at Wettzell. B. Inf. Marées Terr. 137, 10849-10861.

Kroner, C. (2001): Hydrological effects on gravity data of the geodynamic observatory Moxa, J. Geod. Soc. Japan 47(1), 353-358.

Kroner, C. and Jahr, Th. (2006): Hydrological experiments at Moxa observatory, J. Geodyn. 41(1-3), 268-275.

Meurers, B. (2000): Gravitational effects of atmospheric processes in SG gravity data, In: Ducarme, B. and Barthélemy, J. (eds.), 2000: Proc. Workshop: „High Precision Gravity Measurements with Application to Geodynamics and Second GGP Workshop", Luxembourg, 1999, Conseil de L'Europe, Cahiers du Centre Européen de Géodynamique et de Séismologie, 17**,** 57-65.

Meurers, B., Van Camp, M. and Petermans, T. (2006): Correcting gravity time series using rain fall modeling at the Vienna and Membach stations and application to Earth tide analysis, J. Geod. (submitted).

Renka, R. J. (1996): "ALGORITHM 751. TRIPACK: Constrained two-dimensional Delaunay Triangulation Package", ACM Trans. Math. Software, 22, 1, 1-8.

Van Camp, M., Vanclooster, M., Crommen, O., Petermans, T., Verbeeck, K., Meurers, B., van Dam, T., and Dassargues, A. (2006): Hydrogeological investigations at the Membach station, Belgium and application to correct long periodic gravity variations, J. Geoph. Res., in print.

Acknowledgement

Cooperation with Geophysical and Climatological Divisions of the Central Institute for Meteorology and Geodynamics, Vienna, is gratefully acknowledged as well as financial support by Austrian Science Foundation, project P16480-GEO. Thanks to Peter Janac (Vienna City Administration, Municipal Department 45 - Water Engineering) for providing groundwater data.