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Hydrology and Earth System Sciences Discussions

Interactive comment on "The benefits of gravimeter observations for modelling water storage changes at the field scale" *by* B. Creutzfeldt et al.

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Dear Ewald Brückl,

We would like to thank you for your review and for your comments on our paper. We believe that they helped to substantially improve the manuscript and we responded to all comments.

Comment: The authors clearly point out the benefit of accurate gravity data (Super-Conducting & absolute gravity measurements for calibration) as an integral constraint on hydrological parameters, especially water storage changes. They present a sim-

ple, however, powerful model for modelling these gravity changes and demonstrate the close relation between gravity and water storage changes. The paper is a very interesting contribution to HESS. Based on the good results the authors present in their paper, one could ask why gravity has not been integrated more frequently into hydrological monitoring. Therefore the authors should briefly address costs and maintenance of SC gravity meters. Today there are about 30 SC gravity meters in operation at geophysical-geodetic observatories only. Costs for instrument and maintenance exceed most probably the costs for a completely equipped classic hydrological monitoring field (say 10 boreholes, sensors for groundwater level, soil moisture, automated data acquisition, etc.).

Answer: That's a good point. We agree that practical aspects still limit the application of gravimeters for hydrology. Therefore, we will include the following discussion of the use of gravimeter for hydrological applications (P 2240 L7): "Still, practical aspects limit the application of gravimeters for hydrology. SGs are the state-of-the-art relative gravimeters with a temporal resolution of $\sim$1 sec and an accuracy of $\sim$0.1 μGal. However, they are cost-intensive in acquisition and operation. In general, they need a good infrastructure and are operated at a fixed location, although first attempts have been made to take SGs into the field (Wilson et al., 2007). The new SG generation – the iGravTM SG – will improve the applicability of SGs in terms of portability, low drift and usability (GWR, 2009). Absolute gravimeters (FG5 and A10 (Micro-g LaCoste, 2010a, b)) are stable concerning the temporal drift and have the advantage of being portable. The accuracy and temporal resolution is not as high as for SGs (Schmerge and Francis, 2006), but they have already been used to study the relationship of gravity and hydrology (Jacob et al., 2009; Jacob et al., 2008). Spring-based gravimeters are relative gravimeters, portable and relatively inexpensive. In the context of WSC, they are used on a campaign-basis to map spatial variation of gravity changes in comparison to a reference point. In general, gravity changes above 10-15 μGal can be detected by these gravimeters, and with very high effort, the detection limit can be lowered to $\sim$2 μGal (Naujoks et al., 2007; Brady et al., 2008; Chapman et al., 2008; Gettings et al., 2008; Pool, 2008). For the sake of completeness, we would like to mention that advances in atom interferometry promise to improve the reliability of absolute gravity measurements and will be available for the geophysical community in the future (de Angelis et al., 2009; Peters et al., 2001). Hence, technical advances in gravimeter technology are necessary in terms of portability, precision and cost-efficiency to tap the full potential of gravimeter measurements for hydrological applications and to make them routinely available to the hydrological community."

However, evaluating the costs of a classical hydrological monitoring system in comparison to gravimeter measurements is difficult, because the overall costs are not only determined by the costs of a gravimeter but also the by the costs of the monitoring system. These costs vary largely and depend also on the geologic settings. They could, for example, be relatively low for an area with a sandy, shallow and homogeneous aquifer, and relatively high for an area with a granitic, deep and heterogeneous aquifer. This might already give an indication of the area of application for gravimeters.

Furthermore, we think that gravimeters can provide a completely new perspective of the hydrological system, because in hydrology we still lack a monitoring system to continuously observe WSC on the field scale and also in the deep vadose zone. Although the very high costs of temporal gravity measurements will limit the application of gravimeters to only a few scientific studies, we think that they are "worth their salt" and I subscribe to the statement of Klemes (1986): "it also seems obvious that search for new measurement methods that would yield areal distributions, or at least reliable areal totals or averages, of hydrologic variables such as precipitation, evapotranspiration, and soil moisture would be a much better investment for hydrology than the continuous pursuit of a perfect massage that would squeeze the nonexistent information out of the few poor anaemic point measurements [. . .] even Lucretius Carus knew two thousand years ago that 'nil posse creari de nilo.'"

Other remarks /questions are:

Comment: How is snow water equivalent derived from snow height? Has snow compaction been considered?

Answer: We will modify this section (L2230 Z4-Z9) to: "The snow water equivalent was computed based on the snow depth and precipitation data. During periods with snow depth greater than zero, we assumed that all precipitation had fallen as snow (SIn). We also assumed that a decline of snow depth was caused only by snowmelt (SOut), neglecting snow compaction. The snowmelt amount was proportionally estimated in relation to the snow depth decline. For each time step, the snow storage is . . ."

Comment: Is the hydrological model purely 1D (in vertical direction) or is horizontal transport also considered?

Answer: The hydrological model is a purely 1D model and estimates WSC over depth. We will mention this and we will include an explanation why we focused on this 1D approach (P 2229 L21): "As a simplifying assumption to approximate the complex and open hydrological system, we consider water storages to vary over depth neglecting lateral variability of water storages. This assumption was motivated by the fact that at the scale relevant for the gravimeter, the variability of WSC over depth is much more important than the lateral variability of WSC. This is given because water storages are controlled by the driving processes like infiltration, evaporation, plant water uptake, deep drainage, groundwater recharge or groundwater discharge, as well as by internal properties of the system such as soil hydraulic properties or macropores. At the scale relevant for the gravimeter, these first order controls of water storages differ significantly over depth while a lateral continuity is given for most of the processes and landscape features." For further discussion of spatial variability and why we choose this approach please refer to the answer to Point 6 of the comments from Peter Bauer-Gottwein.

Comment: It would be very illustrative, if the authors would present one or more representative cross-sections showing the soil, saprolite, and groundwater layers.

Answer: We are not sure what you are referring to by "representative cross-section".

For the underground classification we are referring to the WRR paper by Creutzfeldt et al. (2010) where we also present a figure of a drilling core.

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