Hydrol. Earth Syst. Sci. Discuss., 7, C1412–C1425, 2010
www.hydrol-earth-syst-sci-discuss.net/7/C1412/2010/

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.

B. Creutzfeldt et al.

benjamin.creutzfeldt@gfz-potsdam.de

Received and published: 14 July 2010

Dear Peter Bauer-Gottwein,

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

Comment 1: P2223/introductory review: Electrical resistivity tomography should be mentioned as one alternative. "Cross-borehole geophysics" is not a very precise term. Both crossborehole radar and cross borehole ERT have been used for soil moisture

(e.g. Looms et al., 2008).

Answer: We will mention electrical resistivity tomography. As we are referring to different (cross-)borehole geophysical techniques and also to the combination of ERT and GPR, we will not specify to which particular technique we are referring to.

Comment 2: P2223/L27: There is a strict "footprint rule" (Leiriao et al., 2009): 90% of the gravity signal generated by a thin water layer comes from a circular disk of radius 10 times the vertical distance between the layer and the instrument. So the footprint depends very much on the depth of the hydrological target.

Answer: That's a good point. We will change this section and we will include the "footprint rule" for the hypothetical case of a circular disk. Additionally, we will include the Bouguer approximation, as we cannot expect all hydrologists to know about this. The discussions of hypothetical cases will be extended by discussing the case of the layer not being flat but following the topography. For the Geodetic Observatory Wettzell, e.g., simulation results show that topography increases the value of 42 μGal (Bouguer approximation) to 52 μGal and also the radius of influence will change.

The section will read: "Within the Bouguer approximation, a one meter water mass change in a flat and infinitely extended plate causes a gravity response of 42 μGal. Focusing on where this gravity response is generated in this layer, the study of Leirião et al. (2009) showed that 90% of the gravity signal comes from a circular disk of a radius 10 times the vertical distance between the layer and the instrument. Topography determines the distribution of hydrological masses in space and influences the relationship of WSC and gravity response. For the Geodetic Observatory Wettzell, for example, distributing the infinitely extended plate along the topography, a water mass change of 1 m causes a gravity change of 52 μGal (Creutzfeldt et al., 2008). Hence, the effect of WSC on gravity measurements depends on the topography around the gravity sensor and is also a function of the vertical distribution of mass change below the sensor. Different studies showed that local WSC within a radius of 50 to 150 m around the gravimeter are of primary interest for the local hydrological effect on temporal gravity measurements (e.g., Hasan et al., 2008; Van Camp et al., 2006; Hokkanen et al., 2006; Naujoks et al., 2008; Kazama and Okubo, 2009). The gravity time series thus primarily reflect WSC on the field scale, but the exact sampling volume is difficult to define."

Comment 3: P2224/L18-24: This statement may be confusing. Yes, ground-based time-lapse gravity integrates over a footprint of a certain size (s. previous comment), but that footprint is still much smaller than a typical catchment used in hydrological modeling. Typically, such catchments would be several sqkm or 10s of sqkm in size. A groundbased gravity measurement can not give an "integral signal" over such large domains.

Answer: We agree that the footprint size of a gravimeter is smaller than a catchment of several sqkm or 10s of sqkm. We will slightly modify this section explaining the "integral signal". However, in this section we highlight the integral character of gravimeter measurements integrating over different storages, like, snow, soil moisture or groundwater. We discussed the footprint size in the previous section and mentioning it here would be a repetition. Furthermore, we think that no typical scale exists for hydrological modeling.

Comment 4: The paper operates with two models: The model used to derive "non-gravity" WSC estimates (section 2.4) and the macro-scale model described in section 3.1. The purpose of this division is not entirely clear. The gravity measurements could be very valuable in the cal/val of the section 2.4 model, which is operating at a more appropriate scale for comparison with time-lapse gravity data. It would be interesting to see how well certain parameters of the section 2.4 model are determined by the various available datasets (heads, soil moisture, lysimeter fluxes, gravity etc.). How comparable are the results from the section 2.4 model and the section 3.1 model, given that two different modeling approaches were used and the two models operate at different scales?

Answer: In section 2.4 we introduce the lysimeter-based approach, because the "estimated WSC from the multi-method and multi-site approach presented above can henceforth serve as validation data at the field scale" (P2229 L11-12). This approach combines lysimeter measurements with complementary measurements (hydraulic conductivity, water retention, pump test) and a physically-based hydrological model. Combining measurements with a hydrological model in this way has the advantage that the number of degrees of freedom of the hydrological model can be reduced significantly. In hydrological modeling, the actual evapotranspiration is usually derived from the potential evapotranspiration with assumptions made about the vegetation, e.g. the species, root depth distribution, the state of health and growth. The vegetation is integrated into the model based on parameters such as leaf area index, maximum root depth or root depth distribution. To derive the actual evapotranspiration from the potential evapotranspiration, these different vegetation parameters and their variation over time have to be estimated. In the lysimeter-based approach, WSC including evapotranspiration up to a depth of 1.5 m were measured instead of modeled. Thus, the estimation of the hydraulic parameters for the soil could also be avoided. Modeling the surface soil moisture, would have implied the estimation of at least five different parameters for at least three different horizons. Both examples illustrate that the lysimeter-based approach reduces the degrees of freedom of the hydrological model significantly.

Hence, this is not a "typical hydrological model". It is an approach that integrates different hydrological measurements and the model can be considered as a tool to interpolate WSC measured by lysimeter and groundwater levels. From our perspective, the derived WSC are as close as we can get to reality nowadays in terms of estimating total WSC, and so we consider these WSC as validation data (below we will discuss why we use validation data). We will edit the MS to outline clearly that we consider the estimated WSC changes based on the lysimeter approach as 'measured WSC' also based on the comments of Point 7. The model described in section 3.1 is a lumped and conceptual hydrological model. To this end, a conceptual model was used to reduce calculation time of the model and the number of free parameters. Using a physically-based model would increase the number of parameters and calculation time leading to a more sophisticated calibration algorithm. We agree that physically-based models in combination with gravity data should be given a try in the future, especially for the investigation of the influence of lateral variations of WSC and for the estimation of effective parameters. In this case, more sophisticated calibration techniques should be considered also in combination with other observations to constrain internal model parameters by a multi-objective calibration scheme (e.g., shuffled complex evolution algorithm, Vrugt et al., 2003; Madsen, 2000).

Concerning the scale critics, we think that both model approaches, the physically-based and the conceptual hydrological model, can be applied at different scales. Both model philosophies have been used to study processes on the plot, hillslope and catchment scale (e.g., Seibert et al., 2003; Refsgaard and Knudsen, 1996; Clark et al., 2009; Bronstert, 1999). We do not agree that a physically-based model is "more appropriate" for gravity studies than a conceptual hydrological model. Both model philosophies have advantages but also drawbacks. For example, this study showed that SG observations generalise and simplify the hydrological system and, thus, they are in accordance with the nature of strongly generalized and simplified hydrological models (conceptual models).

We agree that both instruments, an SG and a lysimeter, have a different "sampling volume". However, we compare the results of both measurements systems due to a lack of an alternative technique to observe WSC at the same scale as a gravimeter (see introduction). Lysimeters are considered an appropriate tool for the estimation of field scale properties and thus, can contribute to the upscaling issue in helping to transfer laboratory measurements to the catchment scale (Durner et al., 2008). In this context gravimeters can be considered as next upscaling step.

Comment 5: P2231/L13-15: This statement is confusing. The solution of the inverse problem always requires a solution of the forward problem. I guess the authors want to differentiate between a purely geophysical forward simulation / inversion and a hydrogeophysical forward simulation / inversion (s. Ferré et al., 2009 for terminology) Answer: Will be corrected accordingly by deleting the first sentences of this section and including the discussion of coupled hydrogeophysical inversion in the introduction (P2225 Z16): "Different strategies exist to parameterise/calibrate a hydrological model with geophysical measurements. Frequently, geophysical data are integrated into a hydrological model by inverting the geophysical data to estimate the spatial distribution of geophysical properties. Hydrological quantities are then derived from the estimated geophysical properties and the hydrological model is parameterised/calibrated based on these quantities (uncoupled hydrogeophysical inversion). Contrary to that, a coupled hydrogeophysical inversion framework, as presented by Ferré et al. (2009), directly infers hydrological quantities from geophysical measurements. Geophysical data are interpreted for hydrological research by coupling hydrological and geophysical models during inversion (Hinnell et al., 2010; Rings et al., 2010; Rucker, 2009). For this study, this means in practice that we use (1) a hydrological model with a certain parameter set to calculate the WSC, (2) a geophysical model to calculate the gravimeter response to these WSC and (3) the SG data to assess the parameter set by comparing them to the modelled gravity response."

Comment 6: As I read the paper, the macro-scale hydrological model is a spatially lumped 5- storage model. For each time step, one water storage per compartment is computed. Subsequently, the lumped storage estimates are distributed on a fine grid and each grid cell is vertically displaced according to the DTM. This approach is debatable: It is definitely appropriate for the snow storage, but the other storages (particularly groundwater) will show significant lateral redistribution of water in steep terrain. The authors should discuss this and evaluate how critical these assumptions are for their results. Answer: Based on your comment and taking into account the comments of the other reviewer we will do the following changes: In this study we focus only on WSC over depth and we neglect the lateral variability of water storage. We will explain in more detail why we focus only on the water storage distribution over depth neglecting lateral variability (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, whereas a lateral continuity is given for most of the processes and landscape features."

We will extent the discussion of spatial variability (L2235 Z24 – L2236 Z6). "In this context, gravimeters might contribute to upscale point measurements to the field scale and will narrow the gap to the catchment scale. Hence, temporal gravity measurements should also be investigated in the context of the lateral variability of water storages. For example, as a next step at the Geodetic Observatory Wettzell, the spatial variability of water storages will be investigated along the hillslope using a physically-based hydrological model in a coupled hydrogeophysical inversion framework. Additionally, different concepts of spatio-temporal variability and stability (e.g., Western et al., 2004; Vereecken et al., 2007; Teuling and Troch, 2005; Brocca et al., 2010; Grayson and Western, 1998; Kachanoski and de Jong, 1988; Vachaud et al., 1985; Famiglietti et al., 2008) should be evaluated in the context of gravity observations (e.g., Glegola et al., 2009). These theories were developed and tested based mainly on near-surface water storage, but only very few studies used data from deeper zones (e.g., Pachepsky et al., 2005; Kachanoski and de Jong, 1988). So, it might be problematic to apply them directly to gravity measurements. At the same time, this reveals the potential of gravity measurements to test the developed theories of spatio-temporal variability in combination with different spatial scales not only for near-surface water storages but also for the whole hydrological system."

Comment 7: The model calibration procedure and the procedure to evaluate the value of the different data types are complex and hard to understand from the MS. The authors should make an attempt to simplify the procedures and to improve the clarity of the presentation. As the focus of the MS is on the value of gravity data, it may be sufficient to show just three cal/val runs: One with all the traditional data, one with the traditional data plus the SG measurements and one with the SG measurements only. The key criterion to determine the value of the SG data would be the width of the ensemble spread in the validation period. The authors claim that inclusion of SG data generally reduces model uncertainty. However, from Fig 5, I gather that some traditional data combinations (e.g. BK3TRIME) produce an equally narrow ensemble spread as the SG calibration runs. I must admit, though, that I am not sure I entirely understood Fig 5, as the discussion in the text and the caption are very brief. Answer: To improve clarity of the MS we will include a figure showing the concept and structure of the study and how structure, calibration, evaluation and validation are connected. We will extend the discussion of Fig. 5 and also the caption. Additionally, we will go through the manuscript and will check where we can do simplifications. However, we think it is not possible to realise all suggested simplifications, because then we would loose important aspects of the study.

1. We could simplify the MS by focusing only on the model evaluation without considering the model validation. The results and the value of gravity measurements would be straight forward and easily to interpret (see Figure 3). However, we think that this does not give the whole picture, and in order to gain credibility for the novel measurement method, we perform two different model tests. This might be a reason for the MS being more complicated to read. We perform a model evaluation and the validation of the model. Frequently, a hydrological model is only evaluated by a split-sample test and no further tests are performed. A split-sample test is only a necessary rather than a sufficient testing scheme (Refsgaard and Knudsen, 1996; Klemes, 1986) and including the validation procedure adds another dimension to the MS.

2. From our perspective, it is not sufficient to validate the model performance only by the “width of the ensemble spread” since this value only assesses the precision of the model results but does not make any statement about the accuracy. Therefore, we also compare the model results to the validation data estimated on the basis of the lysimeter approach using the correlation coefficient, the standard deviation and the centred root-mean-square error as suggested in the study of Taylor (2001).

3. We could only reduce the number of different calibrated models in case we had long time series of WSC close to the gravimeter. However, we only have groundwater data from different boreholes at a distance of 200-300 m. The groundwater heads show a different response and it is difficult to decide which groundwater head to use for this study. Furthermore, we measure soil moisture with two different sensors at nearly the same location. Both soil moisture time series show a different course and it is difficult to decide which soil moisture sensors is the “right” measurement. Hence, we think it is not possible to reduce the number of different calibrated models because the data/model selection would be subjective. We think that the presentation of all different data/calibrated models is necessary to discuss the value of terrestrial gravity observation. Validating the models calibrated by classical hydrological data show that some models have higher correlation coefficients (e.g. BK1 or BK1TRIME (Table 5)) while for other models the RMSD (e.g. BK3 (Table 5)) or variation of behavioural model runs (e.g., BK3TRIME) is smaller. This implies that some models perform better in terms of temporal variation whereas other models better predict the amplitude of the signal. This highlights also the problem of point measurements. For example, some measurements are “representative” for an area, whereas other data/models are more site specific. However, only after the measurement/analysis is it possible to determine which data/model is “representative” for an area.

Technical Comments:

Comment 1. Explain that this WSC data is from lysimeters

Answer: Will be corrected as proposed

Comment 2. “generalized” may not be the most appropriate term here. Effective?

Answer: We will delete the term “generalized”, but we will not replace it with the term “effective”, because the word effective is more associated to “effective parameters” rather than “effective information”

Comment 3. Generally replace “water storages” by “water storage” when referring to the state variable in general.

Answer: Will be corrected as proposed

Comment 4. P2223/L25 ff: I don’t understand the logic. The topography around the sensor is only important because it determines “the vertical distribution of mass change below (or above) the sensor”. I guess “but” is the wrong conjunction here.

Answer: Please refer to point 2.

Comment 5. “weather” should be “weathered”

Answer: Will be corrected as proposed

Comment 6. “groundwater data” should be “groundwater head”

Answer: Will be corrected as proposed

Comment 7. “Simnek” should be “Simunek”

Answer: Will be corrected as proposed

Comment 8. Table 1: “Groundwater” should be “Groundwater head”

Answer: Will be corrected as proposed

Comment 9. “Firstly”, “secondly” etc should be “first”, “second” etc.

Answer: Will be corrected as proposed

Comment 10. “larger degree of freedom” should be “larger number of degrees of freedom”

Answer: Will be corrected as proposed

Comment 11. “evolution” should be “evaluation”

Answer: Will be corrected as proposed

References:

Brocca, L., Melone, F., Moramarco, T., and Morbidelli, R.: Spatial-temporal variability of soil moisture and its estimation across scales, Water Resources Research, 46, W02516, doi:10.1029/2009wr008016, 2010.

Bronstert, A.: Capabilities and limitations of detailed hillslope hydrological modelling, Hydrological Processes, 13, 21-48, 1999.

Clark, M. P., Rupp, D. E., Woods, R. A., Tromp-van Meerveld, H. J., Peters, N. E., and Freer, J. E.: Consistency between hydrological models and field observations: linking processes at the hillslope scale to hydrological responses at the watershed scale, Hydrological Processes, 23, 311-319, 2009.

Creutzfeldt, B., Güntner, A., Klügel, T., and Wziontek, H.: Simulating the influence of water storage changes on the superconducting gravimeter of the Geodetic Observatory Wettzell, Germany, Geophysics, 73, WA95, doi:10.1190/1.2992508, 2008.

Durner, W., Jansen, U., and Iden, S. C.: Effective hydraulic properties of layered soils at the lysimeter scale determined by inverse modelling, European Journal of Soil Science, 59, 114-124, 2008.

Famiglietti, J. S., Ryu, D., Berg, A. A., Rodell, M., and Jackson, T. J.: Field observations of soil moisture variability across scales, Water Resources Research, 44, W01423, doi:10.1029/2006WR005804, 2008.

Ferré, T. P. A., Bentley, L., Binley, A., Linde, N., Kemna, A., Singha, K., Holliger, K., Huisman, J. A., and Minsley, B.: Critical steps for the continuing advancement of hydrogeophysics, EOS Transactions American Geophysical Union, 90, 2009.

Glegola, M., Ditmar, P., Bierkens, M. F. P., Arts, R., and Vossepoel, F.: Estimation of the time-lapse gravity errors due to water table and soil moisture variations, SEG Technical Program Expanded Abstracts, 28, 976-980, 2009.

Grayson, R. B., and Western, A. W.: Towards areal estimation of soil water content from point measurements: time and space stability of mean response, Journal of Hydrology, 207, 68-82, 1998.

Hasan, S., Troch, P. A., Bogaart, P. W., and Kroner, C.: Evaluating catchment-scale hydrological modeling by means of terrestrial gravity observations, Water Resources Research, 44, W08416, doi:10.1029/2007wr006321, 2008.

Hinnell, A. C., Ferré, T. P. A., Vrugt, J. A., Huisman, J. A., Moysey, S., Rings, J., and Kowalsky, M. B.: Improved extraction of hydrologic information from geophysical data through coupled hydrogeophysical inversion, Water Resour. Res., 46, W00D40, doi:10.1029/2008WR007060, 2010.

Hokkanen, T., Korhonen, K., and Virtanen, H.: Hydrogeological effects on superconducting gravimeter measurements at Metsähovi in Finland, Journal of Environmental & Engineering Geophysics, 11, 261-267, doi:10.2113/jeeg11.4.261, 2006.

Kachanoski, R. G., and de Jong, E.: Scale dependence and the temporal persistence of spatial patterns of soil water storage, Water Resources Research, 24, 85-91, doi:10.1029/WR024i001p00085, 1988.

Kazama, T., and Okubo, S.: Hydrological modeling of groundwater disturbances to observed gravity: Theory and application to Asama Volcano, Central Japan, Journal of Geophysical Research, 114, B08402, doi:10.1029/2009JB006391, 2009.

Klemes, V.: Operational testing of hydrological simulation models, Hydrological Sciences Journal, 31, 13–24, 1986.

Leirião, S., He, X., Christiansen, L., Andersen, O. B., and Bauer-Gottwein, P.: Calculation of the temporal gravity variation from spatially variable water storage change in soils and aquifers, Journal of Hydrology, 365, 302-309, 2009.

Madsen, H.: Automatic calibration of a conceptual rainfall-runoff model using multiple objectives, Journal of Hydrology, 235, 276-288, 2000.

Naujoks, M., Weise, A., Kroner, C., and Jahr, T.: Detection of small hydrological variations in gravity by repeated observations with relative gravimeters, Journal of Geodesy, 82, 543-553, 2008.

Pachepsky, Y. A., Guber, A. K., and Jacques, D.: Temporal persistence in vertical distribution of soil moisture contents, Soil Science Society of America Journal, 69, 347-352, 2005.

Refsgaard, J. C., and Knudsen, J.: Operational validation and intercomparison of different types of hydrological models, Water Resources Research, 32, 2189–2202, 1996. Rings, J., Huisman, J. A., and Vereecken, H.: Coupled hydrogeophysical parameter estimation using a sequential Bayesian approach, Hydrol. Earth Syst. Sci., 14, 545-556, doi:10.5194/hess-14-545-2010, 2010.

Rucker, D.: A Coupled Electrical Resistivity-Infiltration Model for Wetting Front Evaluation, Vadose Zone J, 8, 383-388, doi:10.2136/vzj2008.0080, 2009.

Seibert, J., Rodhe, A., and Bishop, K.: Simulating interactions between saturated and unsaturated storage in a conceptual runoff model, Hydrological Processes, 17, 379-390, 2003.

Taylor, K. E.: Summarizing multiple aspects of model performance in a single diagram, Journal of Geophysical Research, 106, 7183–7192, 2001.

Teuling, A. J., and Troch, P. A.: Improved understanding of soil moisture variability

dynamics, Geophysical Research Letters, 32, L05404, doi:10.1029/2004GL021935, 2005. Vachaud, G., Passerat De Silans, A., Balabanis, P., and Vauclin, M.: Temporal stability of spatially measured soil water probability density function, Soil Science Society of America Journal, 49, 822-828, 1985.

Van Camp, M., Vanclooster, M., Crommen, O., Petermans, T., Verbeeck, K., Meurers, B., Dam, T. v., and Dassargues, A.: Hydrogeological investigations at the Membach station, Belgium, and application to correct long periodic gravity variations, Journal of Geophysical Research, 111, B10403, doi:10.1029/2006JB004405, 2006.

Vereecken, H., Kamai, T., Harter, T., Kasteel, R., Hopmans, J., and Vanderborght, J.: Explaining soil moisture variability as a function of mean soil moisture: A stochastic unsaturated flow perspective, Geophysical Research Letters, 34, L22402, doi:10.1029/2007GL031813, 2007.

Vrugt, J. A., Gupta, H. V., Bastidas, L. A., Bouten, W., and Sorooshian, S.: Effective and efficient algorithm for multiobjective optimization of hydrologic models, Water Resources Research, 39, 1214, doi:10.1029/2002wr001746, 2003.

Western, A. W., Zhou, S. L., Grayson, R. B., McMahon, T. A., Blöschl, G., and Wilson, D. J.: Spatial correlation of soil moisture in small catchments and its relationship to dominant spatial hydrological processes, Journal of Hydrology, 286, 113-134, 2004.

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 7, 2221, 2010.