Soil moisture measurement and simulation and their impact on gravimetric measurements

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1. Abstract

An interdisciplinary research project which comprises scientists from hydrology, hydrogeology, geophysics and soil sciences has been launched in the neighbourhood of the Geodynamical Observatory Moxa in Germany. For this project the small (Ac 2 km²) catchment which surrounds the observatory has been instrumented with soil moisture and groundwater probes at various locations as well as additional precipitation gauges and a climate measurement station for monitoring of climatological and hydrological parameters in high spatial and temporal resolution. Secondly, a fully distributed and spatially high resolved hydrological model, based on the modelling system J2000, has been set up for continuous simulation of the hydrological processes in the catchment in daily and hourly time steps.

The main purpose of the project was to explore the hydrological influence on the gravity change monitored by a high sensitive superconducting gravimeter, which is part of a world wide network of similar instruments. The gravimeter readings show significant influence of groundwater, soil water contents and snow coverage on the measurements. Those influences interfere with geodynamic signals which are of geophysical interest. However the recorded responses carry interesting information from a hydrological point of view, because a method for direct, integrative and non-invasive measurement of soil water contents and groundwater variations would be available, if the hydrological influence on the response of the gravimeter records could be extracted.

This paper provides an overview of the test site and its geophysical, hydrogeological and hydrological measurement network set up for the project. In particular, the response of the superconducting gravimeter on hydrological variations is shown. Results of the relationship between the gravimetric data, measured hydrological parameters and the modelled hydrological dynamics are also demonstrated.

2. Introduction

A superconducting gravimeter (SG) is an important part of the equipment at the Geodynamical Observatory Moxa in Germany. It is a well known fact that gravimeter data is affected by various environmental influences like barometric pressure, tides, polar motion which can be corrected by regression models. The influence of hydrological variations in the surrounding catchment are, however, is not as well understood. The influence of changing groundwater tables has been discussed by many authors (e.g. Lambert and Beaumont 1977, Kroner 2001, Harnisch and Harnisch 2002). Beside groundwater, there are other sources of influence like soil moisture, snow, interception and sap flow which have not been considered in all details in previous work. The magnitude of the hydrological influences depends on the location of the water mass in relation to the gravimeter, which is somehow problematic in Moxa, because the gravimeter is placed in a building at the end of a steep and more than 40 m high slope on the valley floor of a small catchment. As a result, most of the terrain surface north, west and east of the observatory is higher than the gravimeter's location.

Because the gravity data contain integrated information of hydrological mass shifts (Kroner and Jahr, 2005), the signal can be a valuable source for hydrologists for model assessment and validation. Some preliminary assessments and experiments from scientists from Jena, Göttingen, and Wageningen (NL) have show that the gravimeter signal can be used for hydrological model validation and process studies.

To obtain more information about the soil moisture variations and their influences on the gravimeter data, the catchment was equipped with five FDR probes which record soil moisture variations in different depths on different locations. Additionally a soil mapping campaign was carried out to provide better soil information as a baseline for hydrological modelling.

In addition to these measurements, the hydrological model J2000 (Krause 2002) was parameterised and applied in an hourly mode in the period from the 19th of February to the 4th of October 2004. The period was selected because complete time series were available. Due to the short length of the time period, no model calibration was performed; moreover, the parameters obtained in daily mode in a catchment nearby were transferred. As a result, the model produces a poor fit of the basin's runoff (Figure 1) with a significant overestimation of the high flood peak and the following periods. The basic idea was not to set up a perfect model for the catchment to reproduce the runoff at the outlet but to obtain spatially distributed values of the models state variables. In particular, spatially distributed values of soil water content for the entire catchment were estimated for comparison with measured values to determine if the soil moisture dynamics are reproduced more or less correctly. Additionally, the modelling approach was intended to serve as a baseline to investigate and identify specific model components that need to be modified to be suitable for the small and dynamic catchment of the Silberleite.

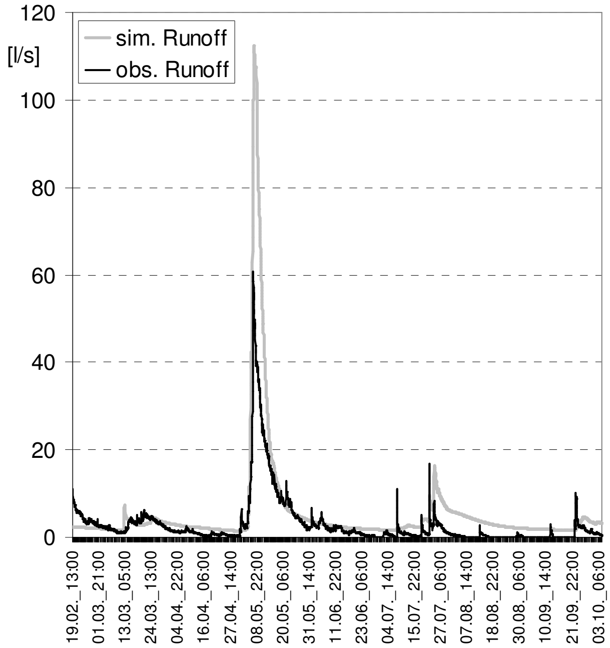

Figure 1: Observed and simulated runoff

Figure 2: V-notch Silberleite

3. The Moxa test site

The Moxa test site is located in Thuringia, Germany 30 km south of Jena. In the 1960s, a seismological observatory was established at the Moxa site near the outlet of a small catchment drained by a small creek, the Silberleite. In 1999, the observatory was equipped with a superconducting gravimeter for geophysical monitoring of the earth's temporal gravity field variations. Because such an instrument is affected by climatological influences (e.g. temperature, air pressure, humidity), a climate station was installed on the roof of the building to monitor rainfall, air pressure, temperature, relative humidity, wind speed and wind direction. The water level of the Silberleite is recorded with a diver beside a V-notch near the observatory (Figure 2) and the runoff volume is measured once per day manually.

The catchment of the Silberleite has an area of 1.9 km² and is shown in Figure 3. It has elevations range between 540 m to 450 m at the outlet. As shown in the map, nearly the whole catchment is covered by coniferous forest and only two small parts are used as agricultural areas (west and east).

The geological underground consists of crystalline schist (Lower Carboniferous) and is strongly fractured in the top layer. Because of tectonic reasons, the fractures are mostly oriented vertically resulting in preferential flow paths for fast infiltration of subsurface water. It has to be noted that the valley floor between the observatory and the Silberleite has been filled up with debris resulting from the construction of the observatory and a tunnel for geophysical measurements. This debris can be considered an ideal and very permeable groundwater aquifer which drains water from/to the stream bed.

The soil types have been mapped recently to produce a high resolved soil map (Scholten et al. 2004) which is based on more than 30 soil profiles. The soils are mostly silty to loamy with partly significant clay fractions and a considerable rock fraction. At the valley floors, groundwater influenced soils can be found. For the entire area, 15 different soil types have been distinguished and parameterised during the mapping campaign.

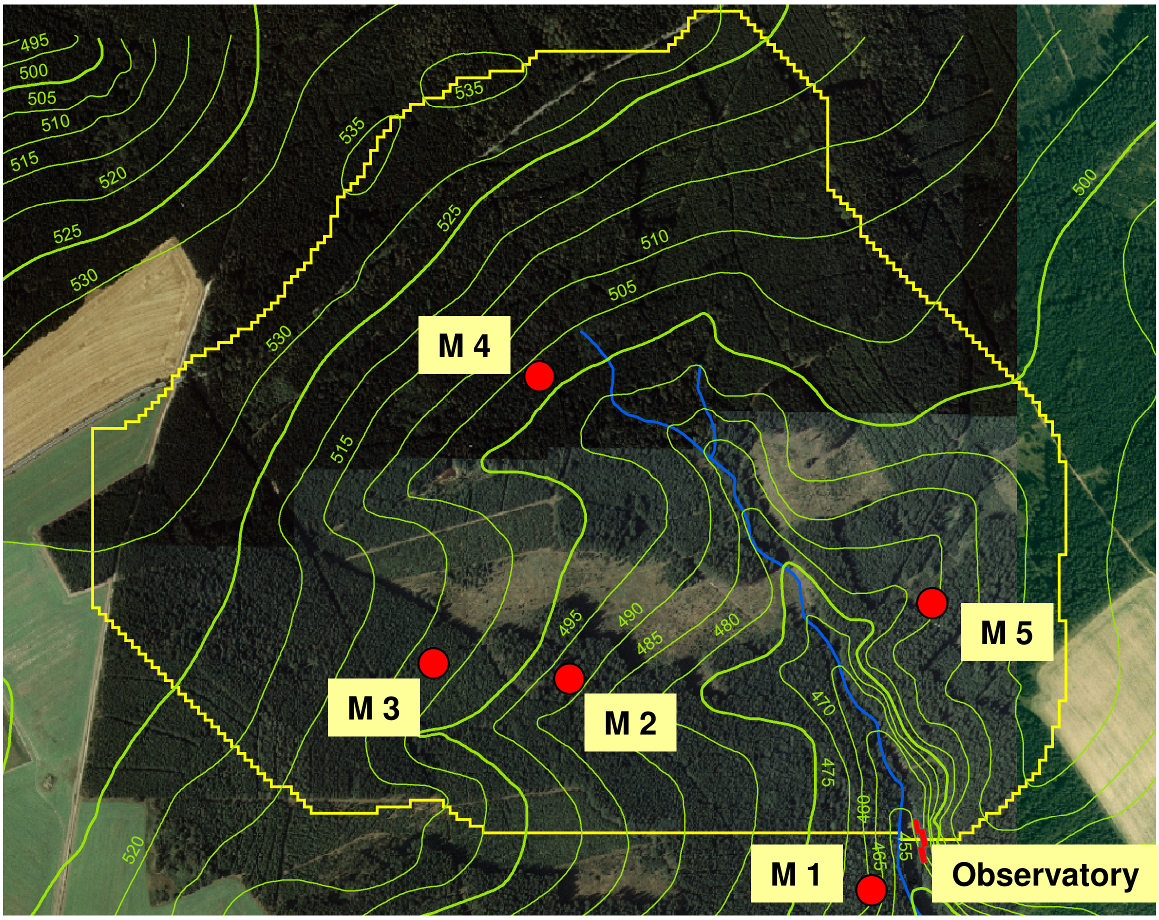

Figure 3: The catchment of the Silberleite, the soil moisture measurement sites and the observatory.

4. The superconducting gravimeter

The superconducting gravimeter (SG), installed in 1999 in Moxa, belongs to a world-wide network of 21 instruments (Crossley et al., 1999) which monitor variations of the earth's gravity field. The principle layout of the SG consists of a Niob sphere which levitates in a defined null position in a magnetic field generated by superconducting coils. Whenever a mass change above or below the gravimeter occurs, the sphere tends to move in direction of the mass increase. The voltage which is needed to keep it at the null position is recorded as relative gravity change. Because of the sensitivity of the instrument, it is affected by various influences such as barometric pressure, earth tides, polar motion, instrumental drift and hydrological influences. For all influences beside hydrology, models exist by which the gravity readings can be reduced resulting in the residual gravity which is referred to in this paper. Because of the complexity and variability of the hydrological processes, it is difficult to apply simple correction terms to remove the hydrologic influences. Some approaches for stochastic correction can be found in Kroner (2001) and Kroner and Jahr (2005). A more promising way would be the use of a hydrological model combined with in situ measurements to simulate all relevant hydrological processes distributed with a certain degree of precision. The development and application of such a model is the main objective of the current project carried out by the authors of this paper.

5. Soil moisture measurements

To provide a base for the assessment of the influence of soil moisture on the gravimeter signal, five Frequence Domain Reflectrometry (FDR) C-Probes have been installed in the catchment. The locations were selected in such a way that an understanding of the distribution of the soil moisture variations could be obtained by the measurements. Therefore, locally distributed sites with different soil types were selected for instrumentation. Unfortunately, the slope east of the observatory, which has the major influence on the gravimeter signal, was not permeable enough for an installation. The FDR installations are marked as red dots in Figure 3.

The FDR-Method is based on the measurement of the dielectrical capacity of the surrounding medium. Soil moisture measurement relies on the fact that the dielectrical constant of the mineral soil (3-5) is significantly different than that of water (~78). The installed probes create an electrical signal with a frequency that depends on the dielectrical constant of the surrounding and can be directly related to soil moisture.

The C-probes (Figure 4, ADCON) allow the installation of up to six single sensors each at different depths. Each probe is installed in the soil in a plastic tube and integrates a radius of 10 cm which is equivalent to a soil volume of 1.9 l. Because the signal strength is decreasing with distance, it can be assumed that 95% of the signal stems from the surrounding 5 cm. During the installation of the probes, great care must be taken to ensure that the soil material is disturbed as little as possible. The uncertainty of such sensors is reported to be less than 5% if they are properly calibrated.

Additionally, each C-probe was equipped with a precipitation gauge with an accuracy of 0.2 mm. The temporal interval of the soil moisture and precipitation recording was set to 15 minutes and the recordings are transferred via telemetry network directly to the observatory from which are can be acquired via a modem. The installation was established in June 2004 and has worked nearly without failures since then.

Figure 4: C-Probe used for soil moisture measurement.

5.1 Soil moisture readings and simulation

In the following paragraphs, the soil moisture readings from the 25th of June to the 4th of October 2004 will be presented and discussed. Additionally, the conceptual model J2000 (Krause, 2002) was parameterised and applied in hourly time steps for the period of the 19th of February to the 4th of October 2004. Due to the short time period, the model was not calibrated very well which is obvious from the comparison of simulated and observed runoff (Figure 1).

The soil module of J2000 simulates the soil water balance integrated over the entire soil profile of each spatial unit with two storage units defined by the different pore volumes: A middle pore storage (MPS) is defined by the useable field capacity and a large pore storage (LPS) is defined by the air capacity of the soil. The water from infiltration is distributed between the storage units based on the saturation of the MPS. As a result, the amount of infiltration to the MPS is higher when there is less water stored in MPS and vice versa. MPS can only be depleted by evapotranspiration, whereas LPS is the source for percolation and interflow. In the following sections, the relative saturation of MPS and LPS together are compared to measured soil moisture time series.

Location M1 is situated in the South-East just beyond the catchment border. The location is approximately 50 m away from the Silberleite, but some 7 to 10 m above the creek itself. The soil was mapped as cambisol with a loamy silt texture with reasonable loess contingents. It has an average depth of 60 to 70 cm. The topsoil has a depth of 4-5 cm, followed by a 45 cm B-horizon, followed by a 5 cm thick C-horizon. The A and B horizons consist of silt with large clay contents, whereas the C-horizon consists of loamy to sandy silt. The rock fraction is 30% in the B and 75% in the C-horizon.

Location M1 was equipped with a C-probe with four sensors in 10, 30, 50 and 70 cm. The recorded volumetric water contents [in %], the precipitation and the simulated volumetric soil water content at the location are shown in Figure 5. From the figure the rising water content with increasing depth can be seen as well as the decreasing dynamics.

The deepest sensor shows a strong reaction at single precipitation events in August and September which it did not show at the beginning in June and July where more precipitation was recorded. The same behaviour can be observed for the sensor in 50 cm in July. This can be interpreted as fast preferential flow through the soil profile through macro pores or by lateral inflow of interflow or a combination of both processes. The modelled soil moisture, which is an integrated value of the whole soil profile, was in the range of the measurements, but shows a damped dynamic. The peaks during the precipitation events are simulated but not reproduced very well. This may be due to the model conceptualisation, which does not consider preferential flow in macro pores.

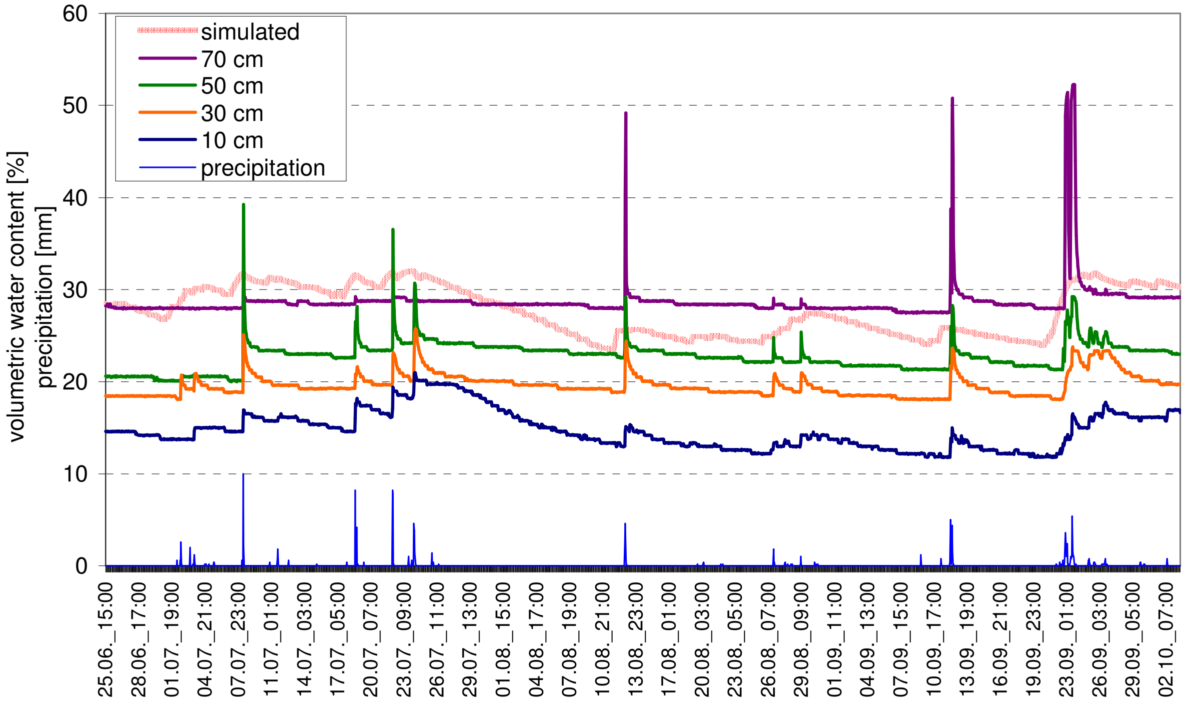

Figure 5: Observed volumetric soil water content in different depths, precipitation and simulated soil water content at location M1.

Location M2 is situated North-West of M1 and about 40 m higher on the slope. The soil was mapped as cambisol with clayey silt texture in the upper horizons and sandy to loamy silt in the C-horizon. It has an average depth of ~ 60 cm. The topsoil has a depth of 7 cm, followed by a 35 cm B-horizon a 15 cm C-horizon. The rock fraction is 15% in A, 22% in B and 30% in the C-horizon. The location was equipped with a C-probe with five sensors covering a depth from 10 down to 60 cm. The observed and simulated volumetric soil water content is shown in Figure 6.

In comparison to M1 this location shows a more dynamic behaviour of the soil moisture, in particular at the upper sensors. This could partly be explained by the higher precipitation rates resulting from a less dense tree cover at this location. A second explanation can be seen in the location up hill, which results in less lateral inflow. Similar to M1, M2 shows a fast reaction of the lower sensors on precipitation. The simulated soil water content at this location shows, again, a damped dynamic and a slight overestimation at the beginning of the period. In the middle, the volumes match with the recordings despite the ridge at the end of August and beginning of September which was only a small peak in the recording. The reason for the ridge in the modelled soil water may be related to the missing macro pore consideration in the model and possible underestimation of interception.

Location M3 is located about 50 m upslope from M2. It is a very flat site at which nearly no lateral inflow is thought to occur. The soil was mapped as cambisol with clayey silt texture in all horizons. It has an average depth of ~ 60 cm, with a topsoil of 6 cm, followed by a 54 cm B-horizon. A C-horizon was not mapped. The rock fraction is 30% in the B-horizon. The observed and simulated volumetric soil water content is shown in Figure 7.

The recordings at M3 exhibit a behaviour which is surprisingly non-dynamic. All sensors show very low fluctuations throughout the entire period. The modelled soil water content is much more dynamic than the readings but is more or less in the same range. A further investigation of the measurement equipment may be needed for this location.

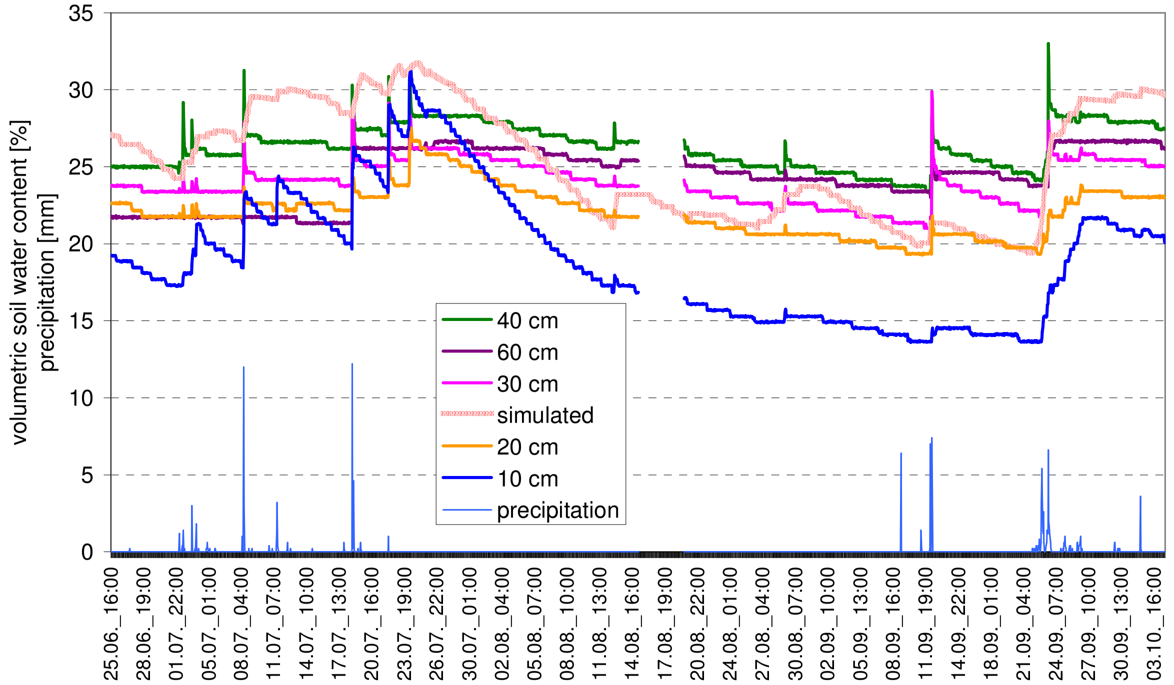

Figure 6: Observed volumetric soil water content in different depths, precipitation and simulated soil water content at location M2.

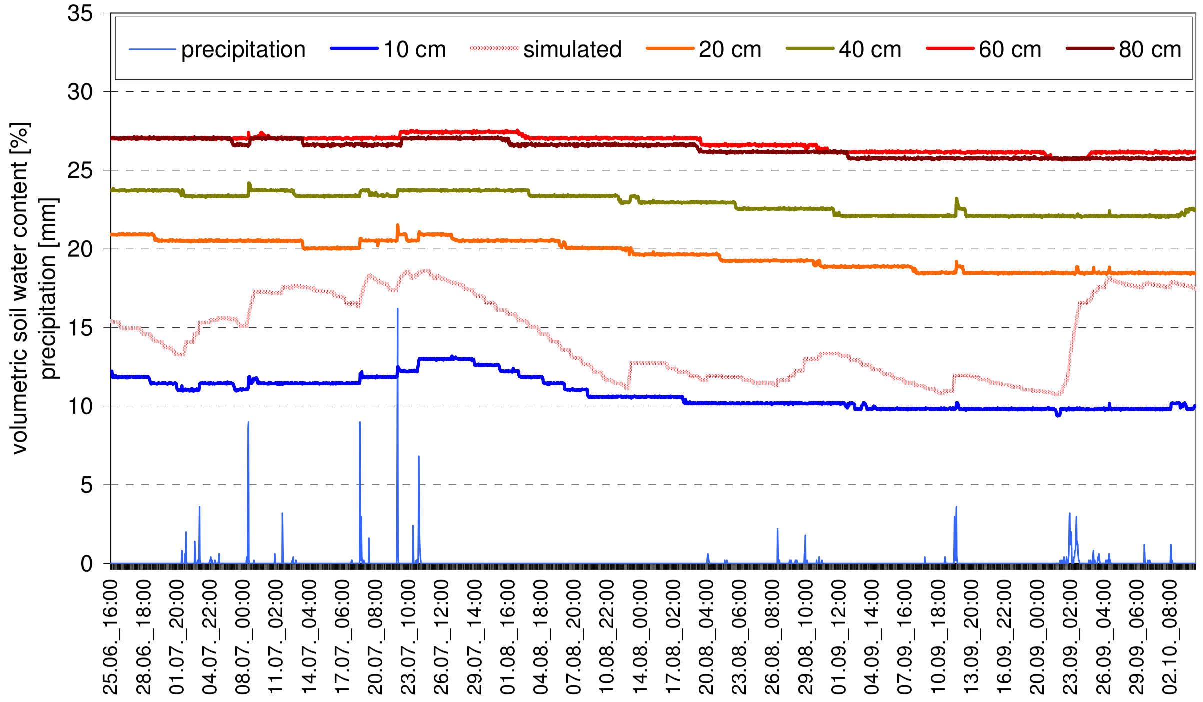

Figure 7: Observed volumetric soil water content in different depths, precipitation and simulated soil water content at location M3.

Location M4 is situated east of the spring area of the Silberleite in the northern part of the catchment about 10-15 m above the creek. The soil was mapped as a stagnic gleysol made of clayey silt in the upper horizons and clay in the lowest one. It has an average depth of 40 to 50 cm, with a topsoil of 5 cm, followed by a 30 cm Bg1-horizon and a 6 to 10 cm Bg2-horizon. A C-horizon was not mapped.

The rock fraction is low with ~10% in the Bg1-horizon. The observed and simulated volumetric soil water content is shown in Figure 8.

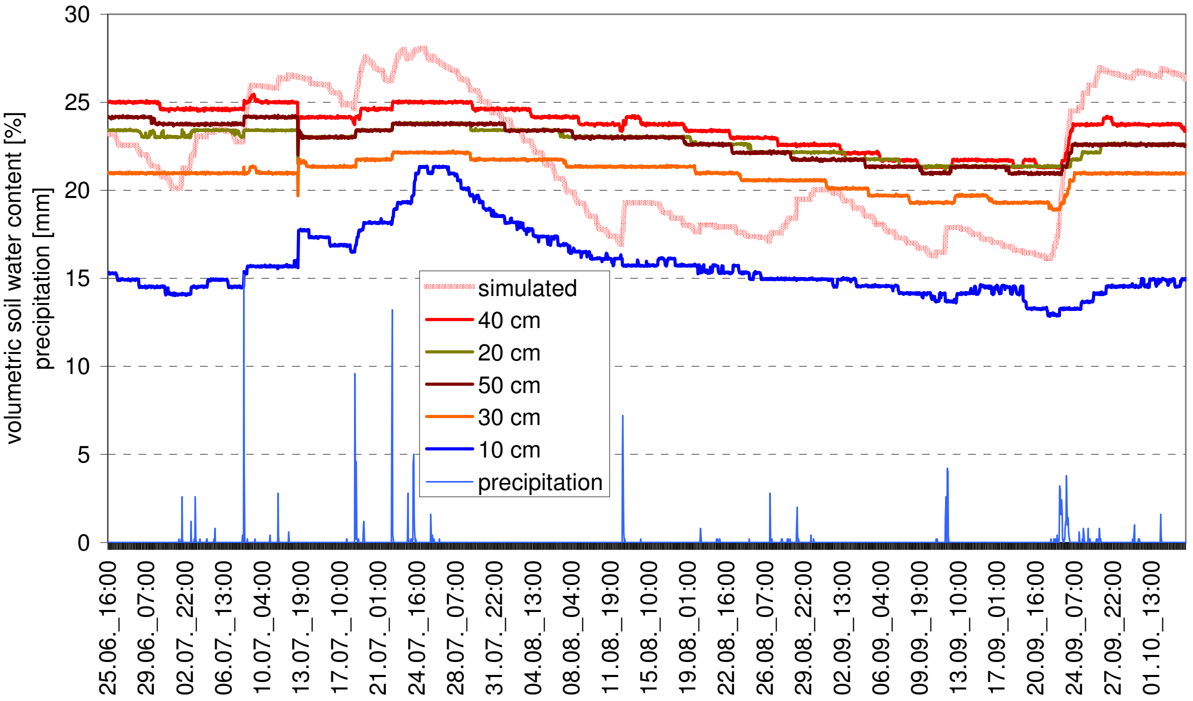

Figure 8: Observed volumetric soil water content in different depths, precipitation and simulated soil water content at location M4.

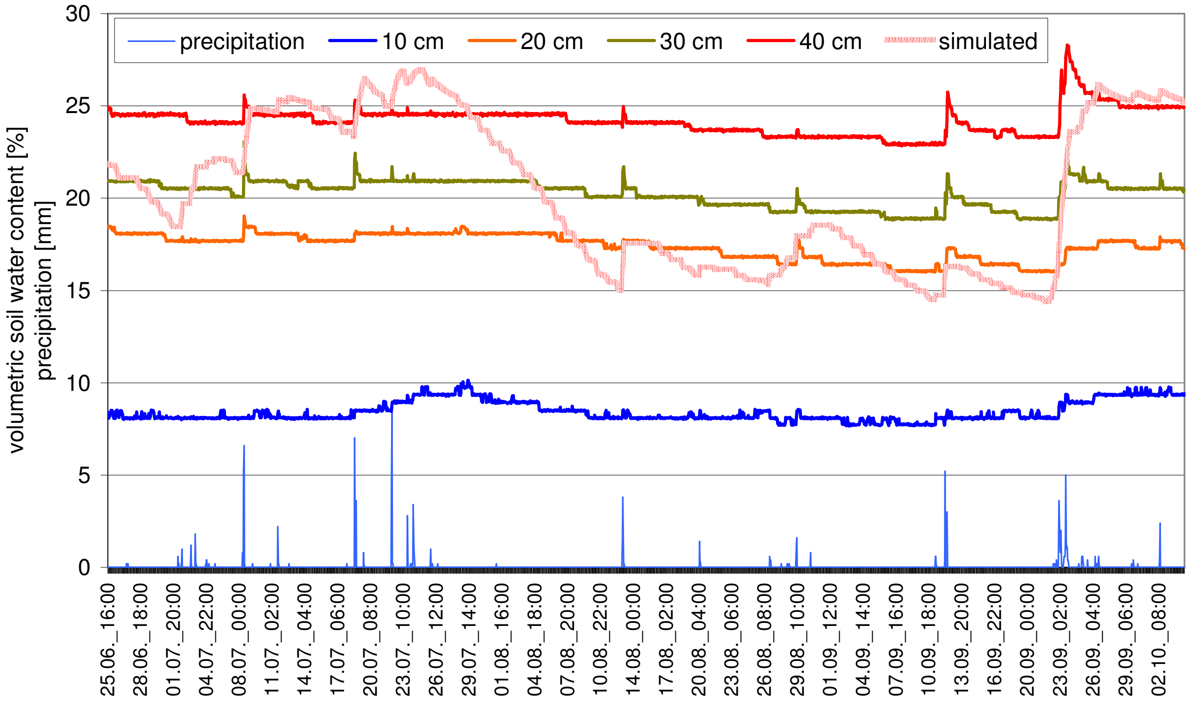

Figure 9: Observed volumetric soil water content in different depths, precipitation and simulated soil water content at location M5.

The recordings at M4 show a dynamic behaviour in the upper 10 cm which is more and more damped with increasing depth. The dynamic reaction of the lower sensors during precipitation events seen at the M1 and M2 sites was not found at this site. This may be due to the stronger saturation throughout the entire period preventing fast preferential flow through the soil. The modelled soil water content is, again, much more dynamic but more or less in the correct range. In particular, the drying trend in the modelled simulation during August and September can only be seen as a slight trend in the recordings. The wetting conditions simulated with the model due to the precipitation at the 23 of September can be observed in the recordings of the lower sensor but with dampened amplitude.

Location M5 is situated in the eastern part of the catchment north and above the observatory. The soil was mapped as a cambisol with silty loam texture in all horizons. The soil has an average depth of 50 to 60 cm, with a topsoil of 22 cm, followed by a 20 cm B-horizon and a 9 to 10 cm C-horizon. The rock fraction is higher than in the other profiles with ~50% in the B-horizon and ~70% in the C-horizon. The observed and simulated volumetric soil water content is shown in Figure 9.

The recordings at M5 show a very steady behaviour in all depths. In the middle and at the end of the period, quick reactions of the lower three sensors on single precipitation events can be observed. The drying up after an event is much slower than it was in M1 and M2. The topsoil of the profile is very dry throughout the entire period and reacts only very slightly on precipitation events. The simulated soil water content at M5 shows a strong drying of the soil profile during July and September resulting in a dynamic behaviour which can not be seen in the sensor readings. For the most part, the modelled soil water content is in the range of the measurements and single events are simulated, but most of the time the amplitude is too large.

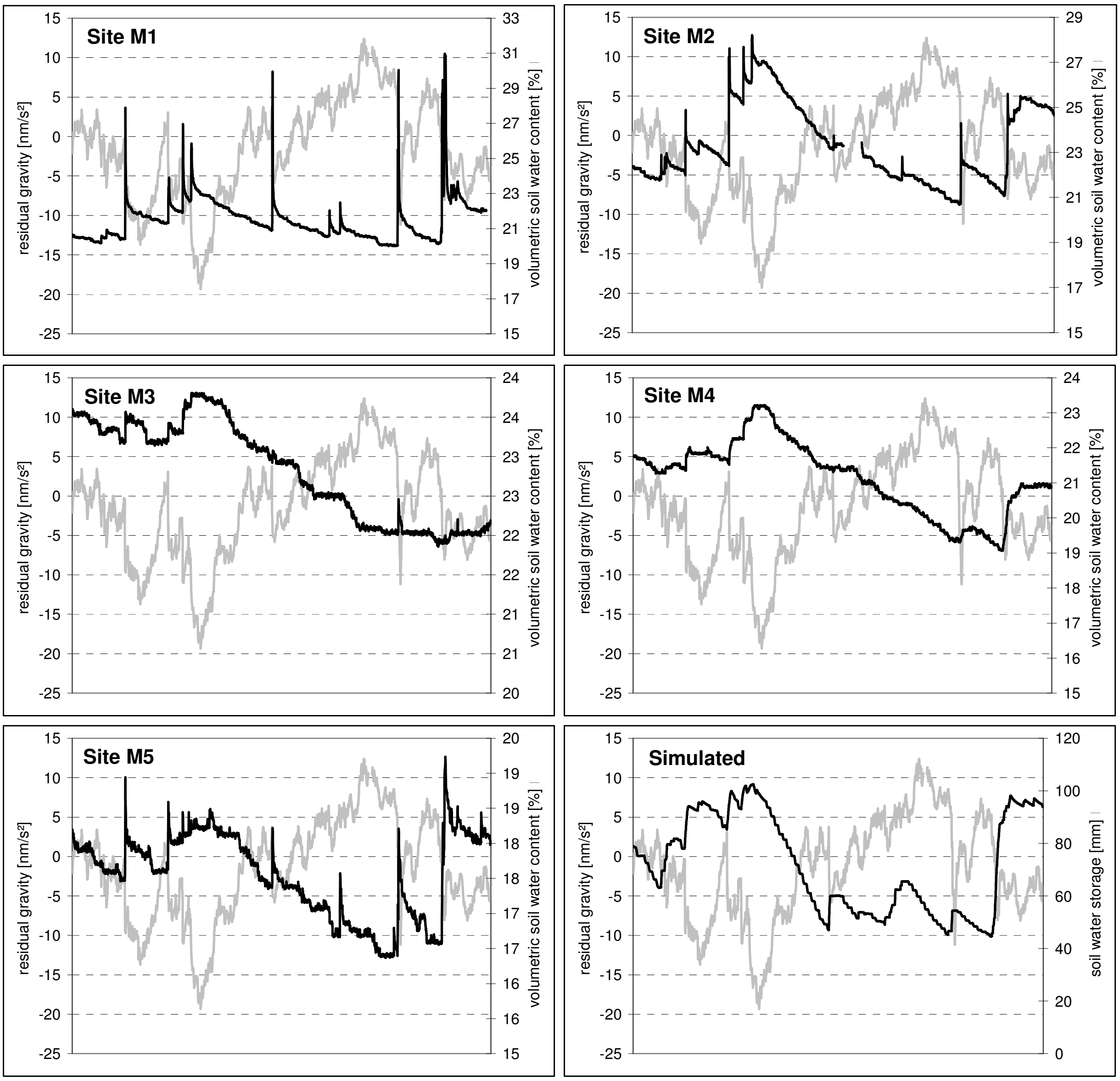

Figure 10: Comparison between residual gravity (grey), measured soil water content (black) at site M1 to M5 and simulated soil water storage as catchment mean for the period between 25.06.04 and 2.10.04.

6. Gravimeter readings and hydrological processes

The next step was the comparison between the residual gravity and the measured and simulated soil water contents. The results of the comparisons are shown in Figure 10. For each plot, a depth weighted mean time series for each site was calculated from the readings of the single sensors and plotted against gravity. It has to be noted that for the second y-axis, different resolutions were set to produce a better view of the dynamics. Additionally, the modelled soil moisture content as a catchment average was used for the comparison. Because M1 and M2 are the closest sites to the observatory, they are of higher interest than M3 and M4 which are further away. Site M5 is also of major importance because it is the only site which lies on the same side of the Silberleite and it has the same soil type as the slope above the observatory.

The inverse behaviour of the gravity reading compared to soil moisture can be clearly seen in the figure. This is most obvious during the continuous decrease of soil moisture of the fairly dry period in the middle of the time series which results in a continuous increase in the gravity data. The heavier rainfalls at the end of the period are replenishing the soil moisture storages leading to a decreasing gravity. This can be seen at the plots of site M2, M4, M5 but also in the simulated soil moisture. From the figure, the immediate reaction of the gravity readings on soil moisture changes can also be seen. This is most obvious at the two low gravity recordings in the first third of the time series. Here, single precipitation events are producing a direct reaction of the gravimeter signal in form of a sharp decrease in the reading that flattens a little bit after several hours.

7. Discussion

A more detailed view of the processes is provided in Figure 11 for twelve days at the beginning of the period. The measured precipitation at the observatory is plotted against the residual gravity and the measured soil water content at site M2.

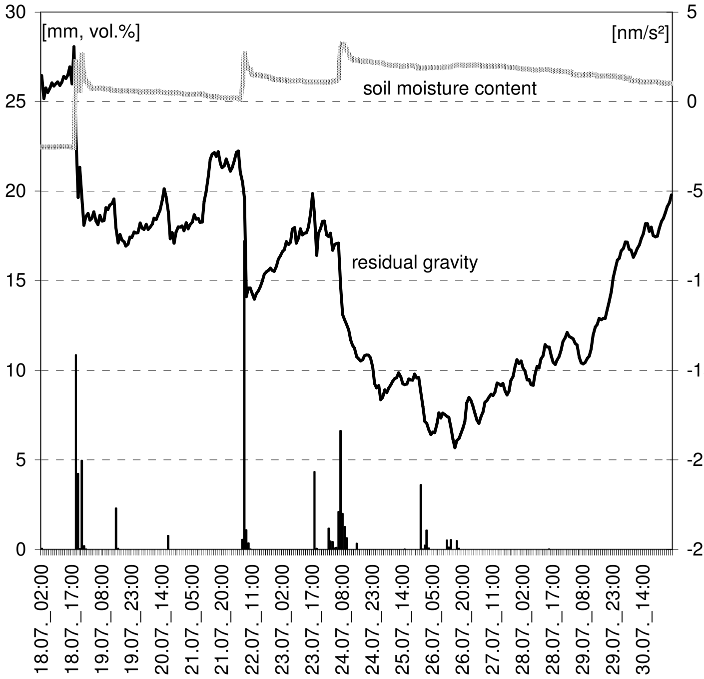

Figure 11: Precipitation, residual gravity and measured soil water content at site M2

This can be interpreted as mass movement from above the gravimeter as a combination of hydrological processes: (1) When precipitation occurs it is stored as interception or on top or inside the topsoil. The mass of the water leads to a sudden decline of the gravity reading. During the rain event nearly no evapotranspiration from this water occurs, but some of the water infiltrates into the soil profile. (2) When precipitation stops the intercepted water is continuously evaporated from the plant surface and the topsoil which leads to an increase in the gravimeter readings because of the mass reduction a top of it. (3) Water which has infiltrated into the soil profile is partly taken out by plant transpiration and partly percolating into the withering zone of the underlying bedrock. As shown at site M1 the process of fast percolation due to preferential flow paths is important in the catchment. Transpiration and percolation leads again to an increase of the gravity reading because of reduced mass. (4) Water in the withering zone percolates partly into the bedrock in fissures and fractures and is partly moving down-slope as interflow, which again leads to an increase of the gravity reading. (5) Once the water has reached a level below the gravimeter level gravity increases due to the additional mass below the instrument. The described behaviour is reproduced during the events at site M1, M2 and M5 and can also be reproduced with the simulated soil water storage. Kroner and Jahr (2005) described an irrigation experiment coupled with measurements in the vicinity of the gravimeter which is further evidence that the assumptions are correct.

Beside soil moisture, other hydrological processes e.g. snow accumulation, interception and groundwater can have significant influence on the gravimeter reading, which are not addressed in this paper but are currently being investigated at the Moxa site by the authors of this paper.

8. Conclusion

In this paper, the influence of soil moisture on the residual gravity monitored by a superconducting gravimeter (SG) in Moxa, Germany was shown. Measured soil moisture readings from five sites have been compared with the residual gravity of the SG. In addition, the distributed hydrological model J2000 was applied in the catchment to (1) provide a comparison between measured and simulated soil moisture values and (2) to provide distributed model results for the entire catchment. The modelling results showed that the J2000 was able to reproduce the range and trend of the soil moisture variations at the five sites. The comparisons of the observations of soil moisture with the J2000 estimates indicate that the model estimates are generally in the same range of the observations but contain a dynamic variability that is generally not observed in the data. Further analysis of the gravimeter signals and the in situ measurements should provide a means for further improvement of the model simulation capabilities in future work.

The findings of the study underpin the importance of soil moisture variations for the explanation of the hydrological influences on the gravimeter signal. A clear reaction of the residual gravity due to soil moisture variations was detected. This was most evident during single precipitation events where an increase of soil moisture could be observed which could be correlated to a sharp drop of gravity at the SG. During longer dry periods when the soil moisture decreases slowly, a slow recover of the gravity signal could be observed.

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