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Detection of hydrological effect on local gravity anomalies

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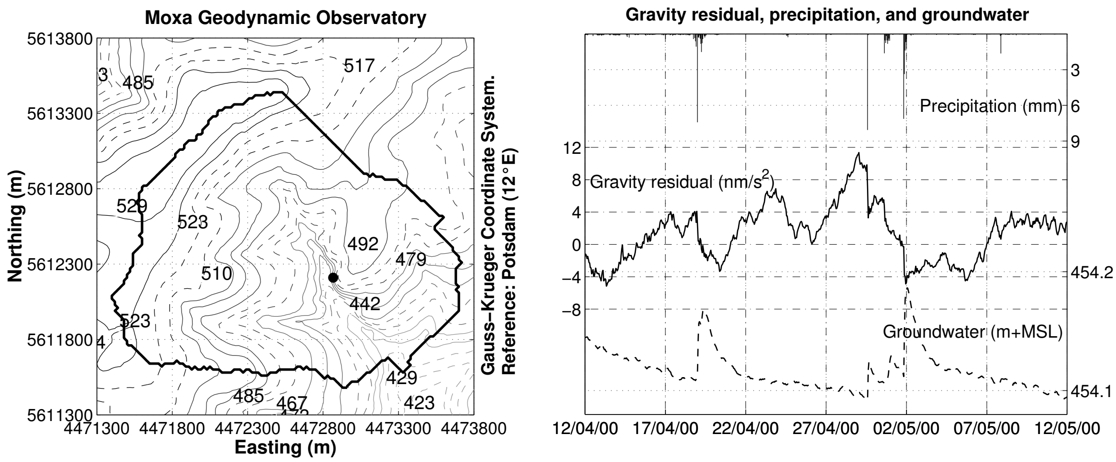
Detecting change in water storage from related temporal variation in gravity has become an important issue for many studies and research related to the Earth and environmental science, oceanography and climatology, and in particular hydrology and geophysics. Finding the relation between water storage and gravity change is promising for hydrologists, in closing the water balance, as well as for geophysicists, in detecting the real long-term gravity change. The Global Geodynamics Project (GGP) began in 1997 with the purpose to record the Earth's gravity field with high accuracy at a number of worldwide stations using superconducting gravimeters (SG). The Gravity Recovery and Climate Experiment (GRACE), jointly implemented by NASA and DLR, is a dedicated twin satellite mission (launched in March 2002) whose objective is to map the Earth's gravity field to high accuracy at monthly intervals. Both GGP and GRACE recognise that tracking the movement of water on and beneath the earth surface is one of the main goals, and thus promise a significant development in hydrological studies. This paper examines the local hydrological effect on gravity at the Geodynamic Observatory Moxa, Germany, by means of time series analysis and distributed hydrological modeling.

Data The data used are from Moxa Geodynamic Observatory (Figure 1.20a). The hydro-meteorological data are collected in the vicinity of the observatory and include hourly precipitation, groundwater, air pressure, temperature, wind speed, humidity, and illuminance and daily surfacewater levels at a V-notch installed in the Silberleite, the small creek in which drainage area the observatory is located. The hourly gravity residuals, hereafter refered to as observed gravity residuals, are obtained after corrections for the Earth tides, polar motion, barometric pressure, and instrumental drift.

Time series analysis From visualization it is clear (Figure 1.20b) that precipitation has a direct and short term effect on gravity, while the effect of long term groundwater change is not always very clear. By means of time series analysis we construct transfer function models (*Box and Jenkins*, 1976) that allow to convert the precipitation and/or groundwater signal to gravity changes. For building the model, we considered two situations: short term response of gravity due to rainfall impulses and long term response of gravity due to slow groundwater changes. The first accounts for high-frequency components, while the latter accounts for low-frequency components in the dynamic behaviour of the total gravity signal.

Distributed hydrological model We used the Soil Moisture Routing (SMR) model to track temporal changes in water storage in the catchment around the gravimeter (Figure 1.20a). The SMR model, originally developed at Cornell University, USA, provides distributed prediction of surface runoff and soil moisture (*Brooks and Boll*, 2004). The model tracks the flow in and out of grid cells using a basic mass balance:

$$D_i \frac{d\theta_i}{dt} = P - ET_i + \sum Q_{in.i} - \sum Q_{out.i} - L_i - R_i \quad (1.1)$$



(a) **(b)**

Figure 1.20: (a) Surrounding topography of Moxa Geodynamic Observatory [lighter and broken lines are contour lines in m+MSL, thick line shows the catchment boundary, the dot indicates the gravimeter location]. (b) Exploring gravity residuals as function of precipitation and groundwater [thick line in the middle is for gravity residuals, lower line for groundwater and upper bars for precipitation].

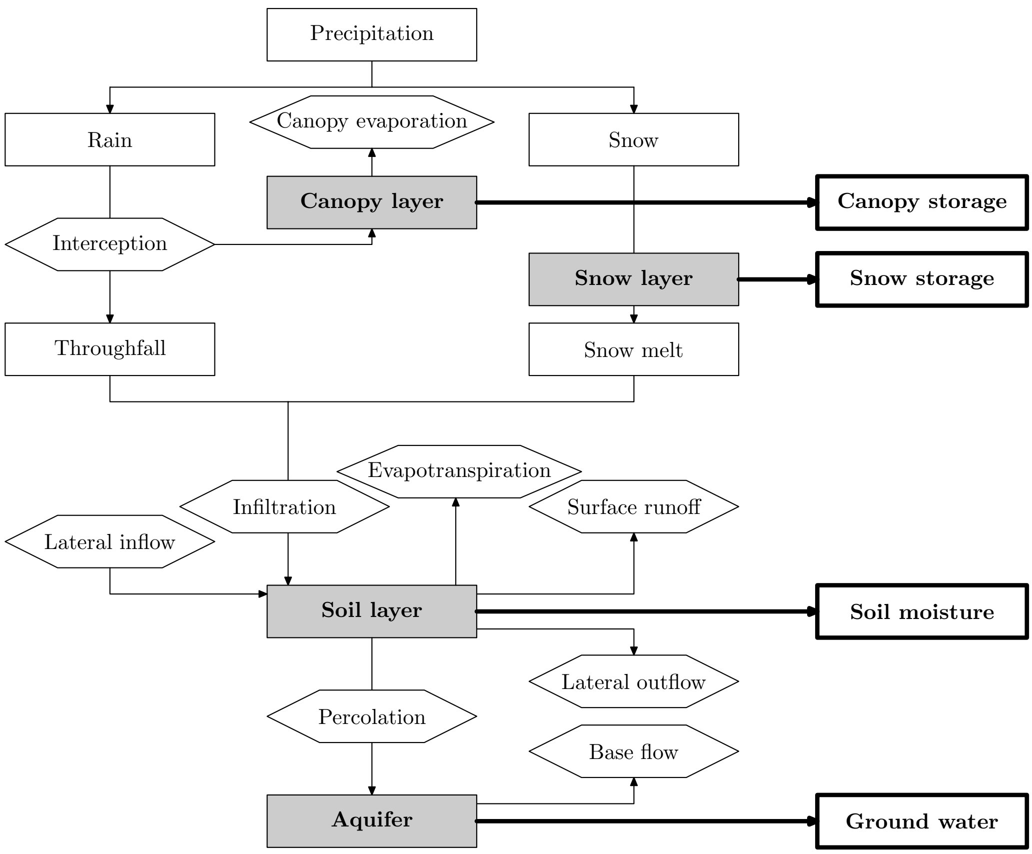


Figure 1.21: Schematic illustrating relevant hydrological processes in the Soil Moisture Routing (SMR) model.

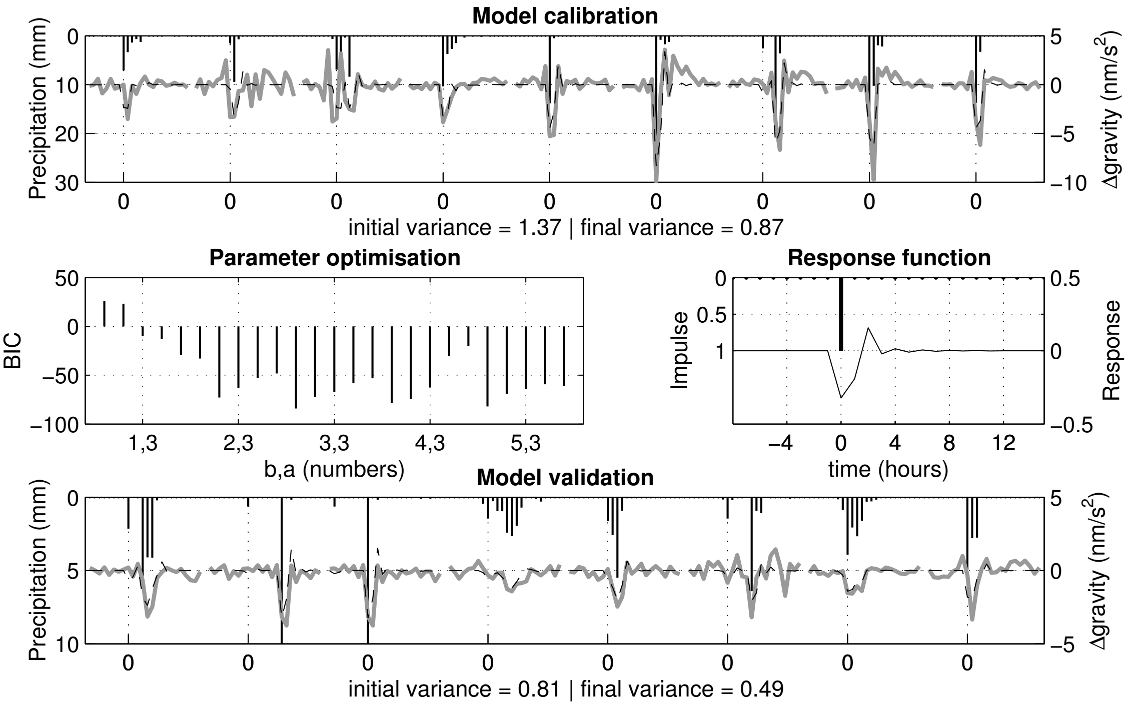


Figure 1.22: Short term gravity response to rainfall impulses [Model calibration showing selected precipitation events (vertical bars) along with observed (gray line) and modeled (dashed line) changes in gravity residuals (top), Model structure characterization (middle-left; a and b represent number of parameters in autoregressive and moving average polynomials of the transfer function (1.3)), Optimized unit impulse response function (middle-right), Model validation showing selected precipitation events (vertical bars) along with observed (gray line) and modeled (dashed line) changes in gravity residuals (bottom)]. Zeros in the calibration and validation plots indicate the starting of the events.

where, i is cell address, D_i is depth to restrictive layer of the cell (cm), θ_i is average moisture content of the cell ($m^3\,m^{-3}$), P is precipitation (rain and snow) (cm), ET_i is actual evapotranspiration (cm), $Q_{in.i}$ is lateral inflow from neighbouring upslope cells (cm), $Q_{out.i}$ is lateral outflow to neighbouring downslope cells (cm), L_i is downward leakage to bedrock (percolation) (cm), and R_i is surface runoff (cm). Note that all the volumetric quantities are presented per area of a grid cell.

Figure 1.21 illustrates the processes in SMR. Calculation of the water balance is facilitated by a GIS, which keeps track of catchment characteristics such as elevation, soil properties, slope, land use and flow direction as well as the moisture stored in each cell at each time step. In this study, the time step was one hour. A detailed description of the model is available in *Boll et al.* (1998) and *Frankenberger et al.* (1999). Modifications to the SMR model include the addition of a canopy layer to simulate interception, and calculation of gravity residuals based on moisture storage in the canopy, snow and soil.

Based on Newton's law of gravitation in a local cartesian coordinate system, the vertical component of gravitation (gravity anomaly) is given by:

$$\Delta g(r) = G \iiint_v \frac{\Delta\rho(r')(z'-z)}{|r'-r|^3} dv \qquad (1.2)$$

with the density difference $\Delta\rho$ of the disturbing mass relative to its surrounding, and the volume element $dv = dx'dy'dz'$ (*Torge*, 1989).

Closed-form solutions of (1.2) are available for a multitude of simple bodies with constant density (*Torge*, 1989). We used rectangular prisms with horizontal limits defined by the pixel size in the DEM and vertical limits of soil depth for soil moisture, snow depth for the snow layer, and canopy interception storage depth for the canopy layer.

Results Considering precipitation events isolated by dry spells, impulse response functions were computed for both gravity and groundwater changes to precipitation. We used a Bayesian Information Criterion (BIC) (*Priestley*, 1981) to optimize the number of parameters in the response functions. We present here the results for gravity response to precipitation impulse (Figure 1.22). During calibration, our impulse response function explains 64% of the variation of the observed gravity change and during validation the explained variance is 61%. If $u_{(z)}$ and $y_{(z)}$ denote the input (precipitation in mm) and output (gravity changes in $\mathrm{nm\,s^{-2}}$), the transfer function in the z-transform domain can be represented as:

$$y_{(z)} = \frac{-0.32 - 0.40z^{-1} + 0.03z^{-2} + 0.08z^{-3}}{1.00 + 0.66z^{-1}} u_{(z)} \tag{1.3}$$

Unlike precipitation effect on gravity, effect of groundwater change is not that straightforward. Gravity, being an integrated signal, contains information related to all kinds of simultaneous mass (re-)distributions. In order to build a transfer function model for long term response of gravity due to slow groundwater changes, we looked at windowed cross correlation between groundwater and gravity for different windows of varying length of 1 day to 1 month at 0 to 5 hours lag. Looking at the histograms of cross correlation coefficient, we find both positive and negative high correlation, as well as no correlation (Figure 1.23). However, from 4 years of data, we find that in more than 50% cases there exists a high negative correlation, while for the rest there is either no correlation or no data or positive high correlation. More investigation is required before we build transfer function models.

The SMR model for the Silberleite catchment was setup using available data sets (DEM, land use, and soil depths). Proper model calibration was hampered because of lack of good quality runoff data. We checked the SMR model results for consistency in computed water balance components and estimated monthly runoff. In general, the model water balance (see Figure 1.24a) is in agreement, for example, with estimates of evaporation/precipitation ratio of $\sim$ 50% (*Peixoto and Oort*, 1992). Monthly runoff was estimated from available surface water level data and compared to modeled monthly runoff (see Figure 1.24b). While judging this verification, we have to keep in mind that no data were collected during high discharge and the fact that our model does not have a deep groundwater component, therefore, regional base flow contribution to total runoff at the weir is not simulated. However, the simulated runoff pattern is more or less in agreement with the observed flow pattern.

Figure 1.25-top compares the observed gravity residuals for a 4-year period (2000–2003) with the modeled gravity changes based on spatio-temporal simulations of the water balance components in the catchment and using (1.2). In general, we can reproduce the observed patterns quite well, although the dynamic range of modeled gravity is about 50% of observed gravity. At this moment, it is not clear what causes this. One possible reason could be that the modeled influence zone of mass distribution around the gravimeter underestimates the true influence zone, due to the fact that deep groundwater dynamics are poorly represented in the hydrological model. The effect of horizontal domain size around the gravimeter is shown in Figure 1.25-bottom to illustrate this point.

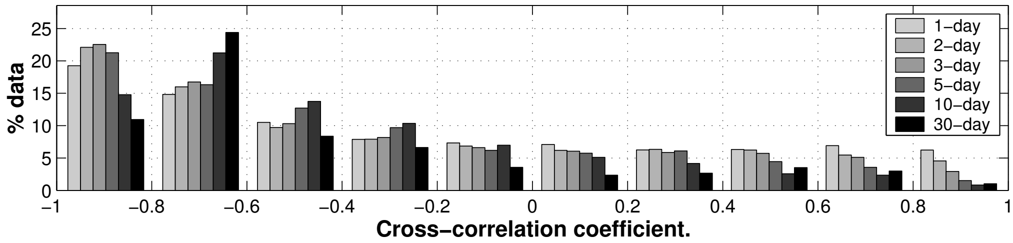
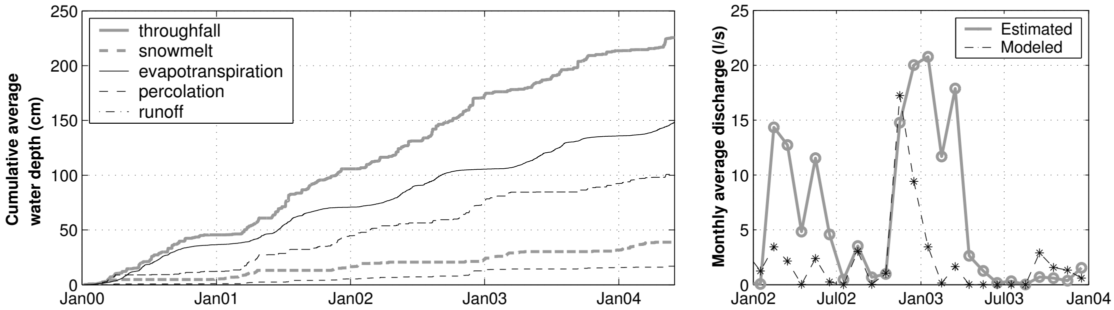


Figure 1.23: Windowed correlation between groundwater and gravity for windows of different time length at lag-0.



(a) **(b)**

Figure 1.24: (a) SMR model water balance [gray lines are for input (throughfall-solid and snowmelt-dashed) and black lines are for output (evapotranspiration-solid, percolation-dashed, and runoff-dotted)]. (b) Model verification: estimated and modeled discharge through V-Notch.

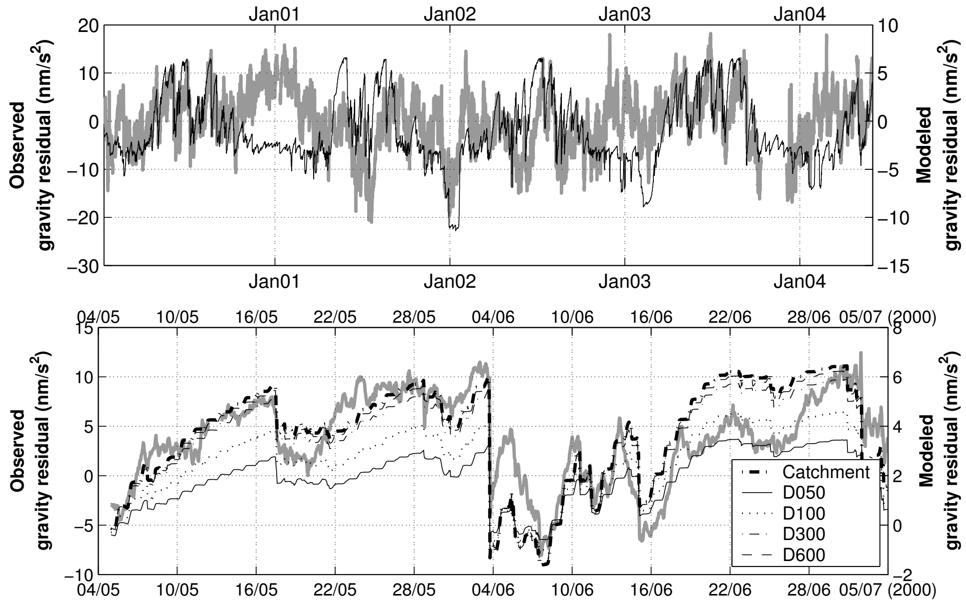


Figure 1.25: Gravity residual: observed (gray) and modeled (black). Modeled residuals containing all storage changes for the entire catchment (top). Effects of different domains in a small time window (bottom).

Conclusion In this paper, both time series analysis and distributed hydrological modeling techniques are explored to explain local gravity anomalies as observed by a superconducting gravimeter at Moxa Geodynamics Observatory, Germany. Both approaches yield encouraging results, and serve complementary objectives. Time series modeling provides us with a simple yet effective technique to correct for precipitation effects on short term gravity residuals. Distributed water balance modeling explains much of the long term behaviour of the gravity signal. From a hydrological persective, in-situ gravity measurements of the kind used in our study offer an intriguing new look at hydrological processes.

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