Groundwater modeling in shales at a steep hill near Jena

R. Dijksma, H.A.J. van Lanen, G. Bier and T. Jahr

Grundwassermodellierung an einem steilen, schieferigen Hangsegment nahe Jena

1 Introduction

Laboratory experiments on the relation between gravimetry and hydrology were conducted on constructed hill slopes with a homogeneous soil and a varying bedrock slope angle (Lyon & Troch, 2007), theoretical concepts such as the Boussinesq equation have been extended (Paniconi et al., 2003) and field experiments have been conducted (Hasan et al., 2006). At the Geophysical Observatory Moxa of the Friedrich Schiller University (Germany; see Figure 1 for the location), the local gravity field has been measured using a superconducting gravimeter since 1999 (Kroner & Jahr, 2006; Hasan et al., 2006; Hasan et al., 2008). This gravimeter has such a high accuracy that local variations in water masses influence the gravimetrical measurements (Kroner & Jahr, 2006). Figure 2 shows gravity residuals versus precipitation and groundwater level variations for a rain event in August 2007. Obviously precipitation events affect shallow and deep groundwater levels and also the gravity residual. Models are needed to correct these disturbances in the gravimetrical signal (Vermue & Van de Voorde, 2005; Dijksma et al., 2006; Kroner et al., 2007). On the other hand, such models can help to understand and quantify the local hydrology and thus hydrological processes on hill slopes. Two hydrological modelling approaches were tested using

1) a cascade of linear reservoirs and
2) a modular three-dimensional finite difference groundwater flow model (MODFLOW).

Zusammenfassung

Wassertransport und Wasserspeicherung an Hangstandorten sind in der Hydrologie von großer Bedeutung. Die Anwendung von supraleitenden Gravimetern unterstützt das Verständnis des Wassertransports an diesen Standorten. Am geophysikalischen Observatorium Moxa der Friedrich Schiller Universität Jena (Deutschland) wurde die Beziehung zwischen hanghydrologischen Prozessen und Gravitätswerten untersucht. Dafür wurde ein lineares Speichermodell zur Quantifizierung der Wasserspeicherung an der Vegetation und in der ungesättigten Bodenzone entwickelt. Darüber hinaus wurde ein Grundwassermodell (MODFLOW) zur Berechnung des Wassertransports im zerklüfteten Schieferuntergrund angewandt. Es konnte eine signifikante Korrelation zwischen Starkniederschlag und dem gravimetrischen Signal gezeigt werden. Auch das Grundwassermodell lieferte zufriedenstellende Simulationen der Fließwege.

Schlagworte: Hanghydrologie, Gravimetrie, Kluftwasser, Grundwassermodellierung, Linearspeicher.

Summary

Water flow and water storage in hill slopes have a strong interest in the hydrological scientific community. The use of the gravimetrical signal of superconducting gravimeters can help to understand water flow in such areas. At the Geodynamic Observatory Moxa of the Friedrich Schiller University Jena (Germany), the relation between hill slope hydrological processes and gravity residuals are investigated. For this purpose a linear reservoir model was developed to quantify canopy storage and storage changes in the unsaturated zone. A groundwater flow model (MODFLOW) was developed to quantify flow in fractured shales. Cross correlation showed significant gravimetrical response on heavy precipitation events after a dry period. The groundwater model simulated the expected flow patterns reasonably well.

Key words: Hill slope hydrology, gravimetry, fracture flow, groundwater modelling, linear reservoirs.

The elevation in this small catchment (2 km^2) varies from 450 to 540 m + ASL, with the steepest slope (up to 30º) directly east of the observatory (NAUJOKS et al., 2010). The land use is predominantly coniferous forest. Mean annual amount of precipitation is 730 mm, mean annual evapotranspiration is 524 mm. The rocks originate from Lower-Carboniferous and consist of > 100 m highly consolidated, intensively folded and fractured shales. Two faults dissect the catchment, which will act as hydraulic conductors. From surface downwards, a thin layer of clay loam (0.3 m), a layer of intensively fractured and oriented shales (0.5 m), and a layer of fractured shale with narrow fractures (0.3 m) can be found. In the Silberleite valley, a thin layer of natural valley fill (0.2 m) is found, and at the observatory, there is an artificial layer of valley fill (0–3 m). This artificial layer was used to flatten the area.

2 Modeling

2.1 Cross correlation

A cross correlation was performed between data series to express relations between parameters. The cross correlation was performed between the following data series:
- gravity residual and precipitation
- gravity residual and groundwater level below gravimeter
- precipitation and Silberleite discharge

In Figure 3 the dotted blue lines indicate significance of the correlation. A clear undulating pattern is visible. Possibly this pattern is a product of filtering of the gravity signal (e.g. filtering for ocean tides). There is a small but significant correlation between gravity residual and precipitation (Figure 3a). The reaction is (almost) direct after a rain event, reducing gravity residual because of increased mass above the gravimeter. Groundwater also reacts fast (within a few hours), but the impact is limited (Figure 3b). Highest correlation between precipitation and discharge is at approximately 30 hours (Figure 3c). This is due to storage in the total catchment.

2.2 Cascade of linear reservoirs

Water storage and water flow are visualized in Figure 1b. Figure 4 shows the canopy and unsaturated zone reservoirs (HUIJBEN, 2011). GERRITS (2010) indicated that there is not a universal canopy parameter. But, since some coniferous trees stand almost directly above the gravimeter, and as such influence the gravity residual, the canopy storage on this experimental site should be described by a reservoir. The number of reservoirs was reduced to only three reservoirs (canopy, soil layer and parent material), in order to reduce the number of parameters that had to be optimized. The outflux of the lowermost reservoir was used as influx for the groundwater flow model.

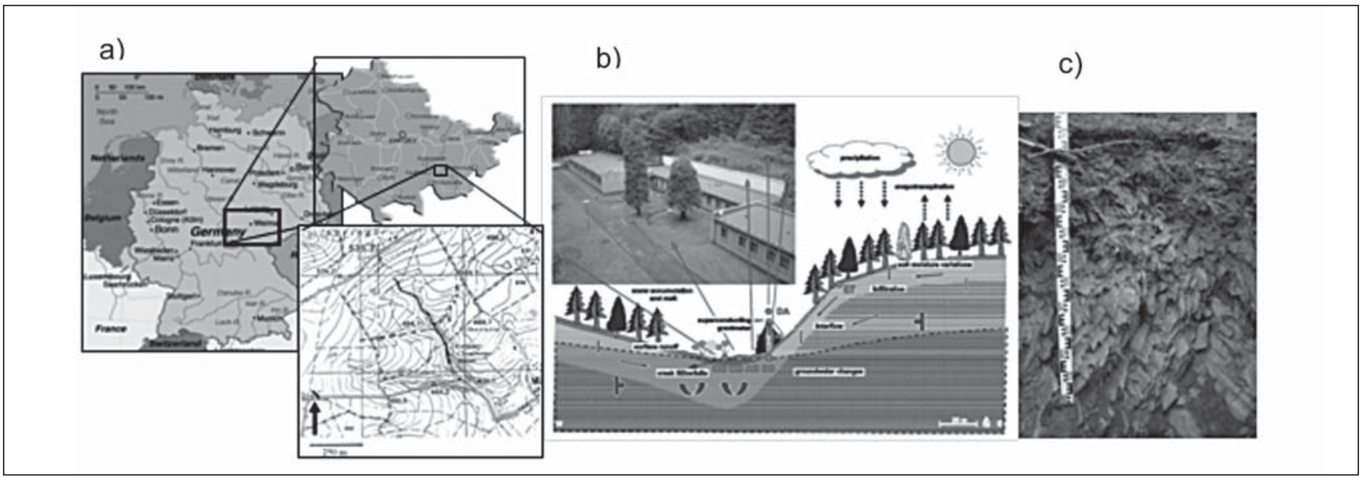

Figure 1: a) Location of Geophysical Observatory Moxa in Germany (Thüringer Landvermessungsamt, 1999), b) possible flow paths around the observatory (NAUJOKS, 2008) and c) impression of the soil and underlying shales

Abbildung 1: a) Lage des geophysikalischen Observatoriums Moxa (Thüringer Landvermessungsamt, 1999), b) mögliche Fließpfade am Observatorium (NAUJOKS, 2008) und c) Darstellung des Bodens und der darunterliegenden Schieferschicht

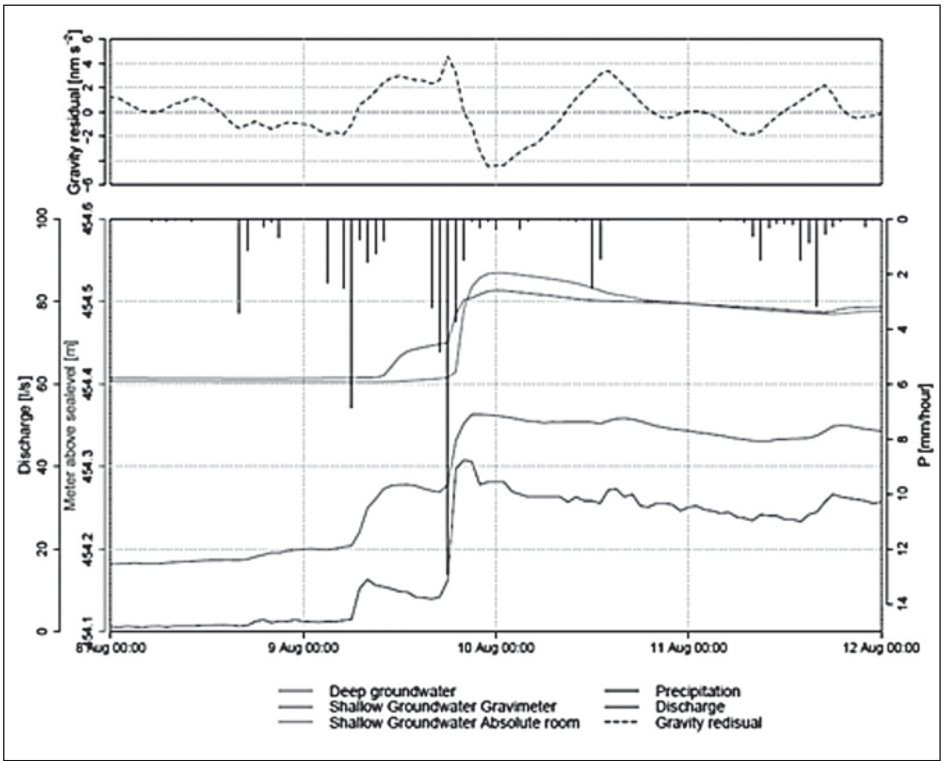

Figure 2: Gravity residuals, precipitation and water levels, period 8–12 Aug 2007
Abbildung 2: Gravitätsdifferenz, Niederschlag und Wasserstände der Periode 8.–12. Aug. 2007

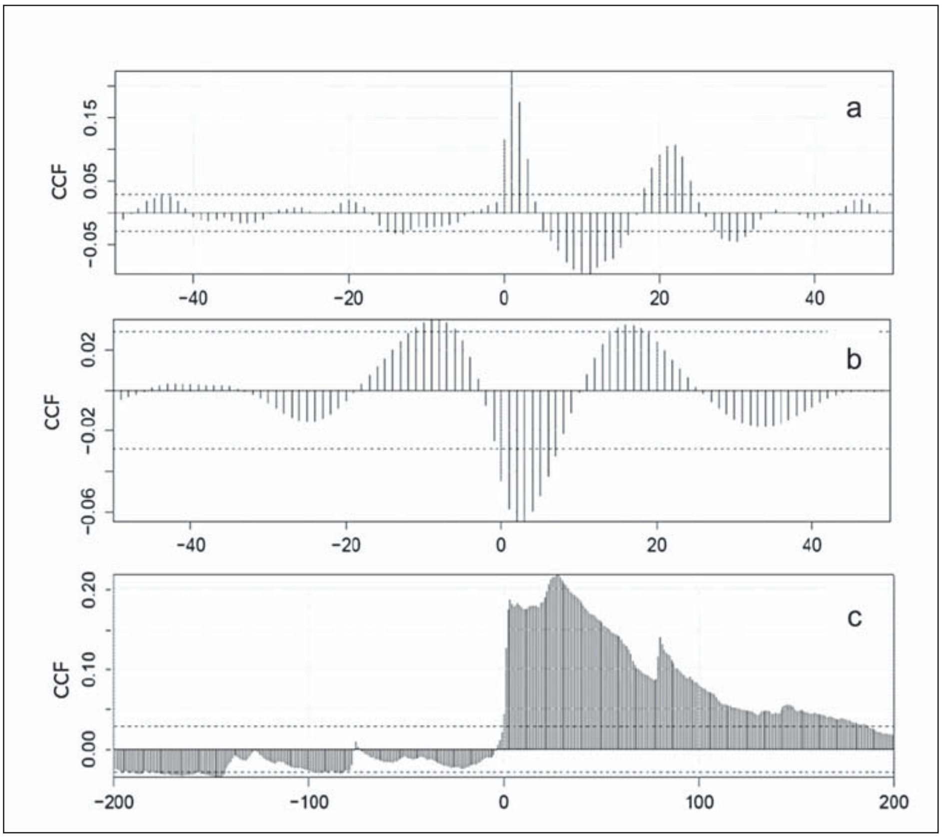

Figure 3: Cross correlation between a) gravity residual and precipitation, b) gravity residual and groundwater below the gravimeter and c) precipitation and Silberleite discharge for the period Feb–Aug 2007
Abbildung 3: Kreuzkorrelation zwischen a) Gravitätsdifferenz und Niederschlag, b) Gravitätsdifferenz und Grundwasserstand und c) Niederschlag und Abfluss Silberleite der Periode Feb.–Aug. 2007

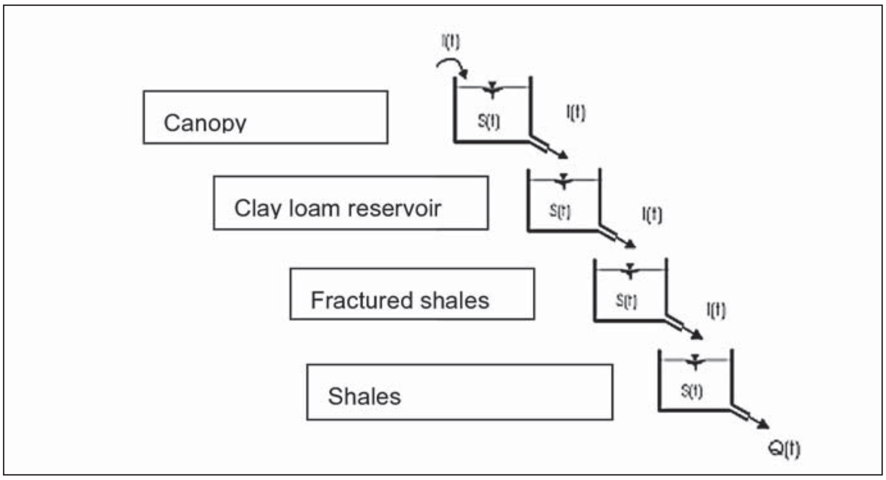

Figure 4: Schematic representation of the reservoir model (HUIJBEN, 2011)
Abbildung 4: Schema des Linearspeichermodells (HUIJBEN, 2011)

2.3 Three dimensional finite difference model MODFLOW

A groundwater flow model (MODFLOW) was developed to describe saturated flow not only in the valley fill, but also in the surrounding hills (including fractured bedrock). Grid size is 5 x 5 m. This dense grid was chosen because of the importance of mass variations in the vicinity of the gravimeter. In order to limit the number of grid cells, only the south-eastern tip of the Silberleite was modelled (see Figure 5).

The groundwater model is divided in 5 layers. Table 1 shows the properties of the model layers. Model layer 3 (shales with clay) can only be found on the western slope and model layer 4 (shales with fractures) only on the eastern slope. The properties shown are the result of a calibration performed with an automated parameter calibration module in GMS (PEST).

3 Results

BERGSMA (2012) showed that MODFLOW can become unstable when a low porosity/low permeability aquifer is overlain by an high porosity/high permeability aquifer, especially in combination with steep slopes. Under base flow conditions water will be discharged through fractures in the poorly weathered shales (layer 5), under wet conditions also highly fractured shales (layer 3 and 4) will act as aquifer. To

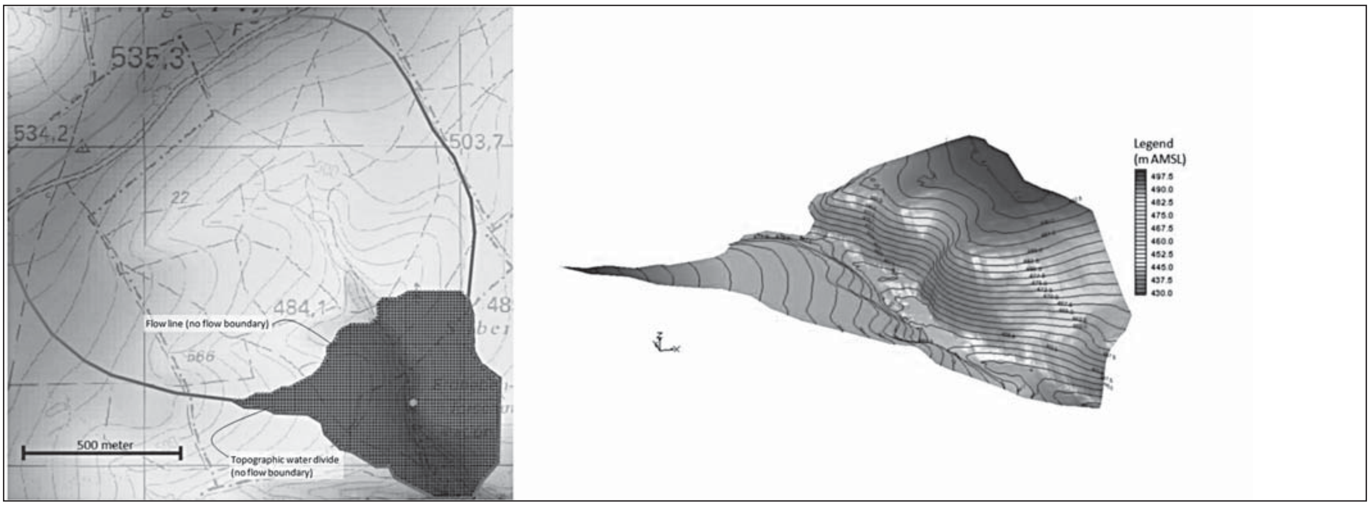

Figure 5: a) Topographical map with elevation, catchment boundary (grey line), model area (black grid) and gravimeter location (green dot), and b) three-dimensional image of the surface level of the modelled area
Abbildung 5: a) Topografische Karte der Geländehöhen, der Gebietsgrenzen (graue Linie), des Modellbereichs (schwarzes Rechteck) und der Gravimeterstandorte (grüne Punkte) sowie b) dreidimensionale Darstellung der modellierten Oberfläche des Modellbereichs

Table 1: Properties of all model layers
Tabelle 1: Eigenschaften der Modellbereiche (Schichten)

layer	material	thickness (m)	k_h (m d^{-1})	k_v (m d^{-1})	specific yield	confined/ convertible
1	artificial valley fill	0–3.5	30	40	0.15	convertible
2	natural valley fill	0.2	1	1.5	0.15	convertible
3	shales with clay	0.8	9	100	10^{-6}	confined
4	fractured shales	0.4	7	0.01	10^{-6}	confined
5	bedrock	60	0.1	0.01	10^{-6}	confined

avoid model instability, layer 3–5 were considered as confined aquifers, where results were improved by admitting relatively high piezometric heads in layer 5 without rewetting layer 3 (west slope) or layer 4 (east slope). Figure 6 shows measured and simulated groundwater levels directly underneath the gravimeter (Figure 6a) and the transient simulated groundwater flow (Figure 6b). The model is capable of simulating the response of the groundwater level, but is too sensitive during very wet conditions (May 2007). Under base flow conditions model results indicate that groundwater flow is directed to the lowest part of the catchment, i.e. southeast of the observatory.

4 Conclusions

Although additional work is needed, we can conclude that under base flow conditions water will flow through fractures in shales, during peak flow water will flow downhill. This, and the canopy storage, influences the gravimetrical signal. The coupled model helped us to get a grip on the flow patterns. As such gravity helps to understand hydrological processes and hydrology helps to improve gravimetrical data.

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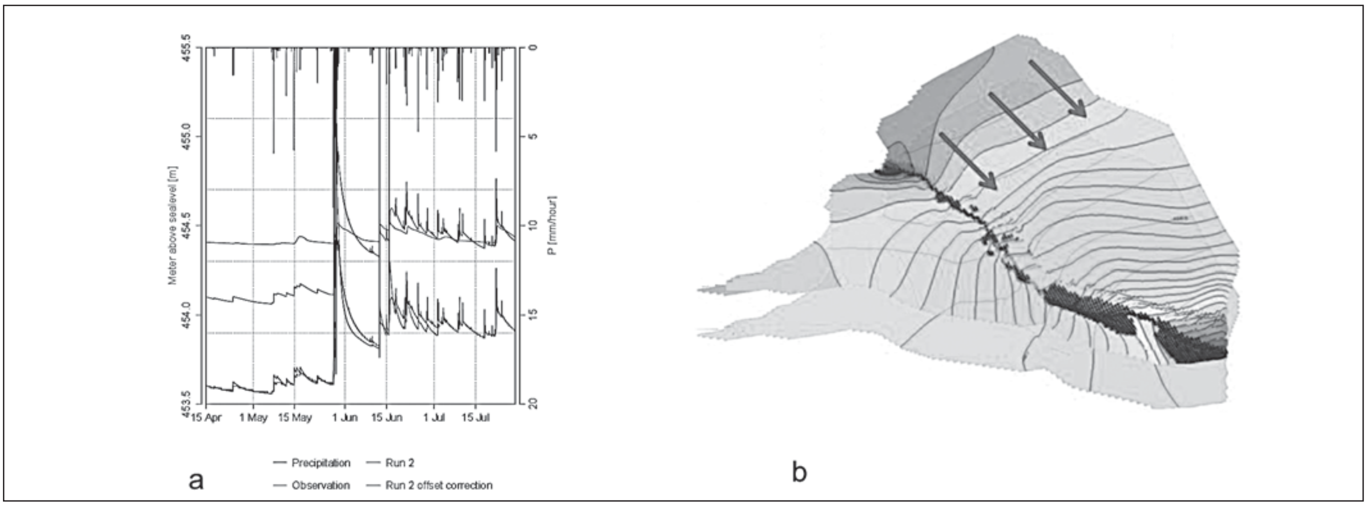

Figure 6: Model results as a) measured and simulated groundwater levels underneath gravimeter (2007) and b) transient simulated groundwater flow
Abbildung 6: Modellergebnisse: a) beobachteter und simulierter Grundwasserspiegel unterhalb des Gravimeters (2007) und b) instationär simulierter Grundwassertransport

References

BERGSMA, T (2012): Modelling the hydrology around the Moxa observatory – towards an understanding of the Earth's gravity field. Masterv thesis Wageningen University, Netherlands.

BROER, M (2008): Modeling groundwater flow with a linear reservoir model in the Silberleite catchment, Moxa, Germany. Field work and hydrological modelling. Master thesis Wageningen University, Netherlands.

DIJKSMA, R., H.A.J. VAN LANEN, S. HASAN, C. KRONER, P.A. TROCH (2006): Relation between distributed water storage and local gravity at Moxa (Germany). In: Unesco-IHP report 'Uncertainties in the monitoring-conceptualisation-modeling sequence of catchment research'. Luxembourg. 75–79.

GERRITS, M. (2010): The role of interception in the hydrological cycle. VSSD, Delft.

HASAN, S., P.A. TROCH, J. BOLL, C. KRONER (2006): Modelling the hydrological effect on local gravity at Moxa, Germany. J of Hydrometeorology, 7, 346–35.

HASAN, S., P.A. TROCH, P.W. BOGAART, C. KRONER (2008): Evaluating catchment-scale hydrological modelling by means of terrestrial gravity observations. Water Resources Research 44 (8).

HUIJBEN, W. (2011): Towards a physical understanding of the hydrological situation around the geodynamic observatory Moxa, Germany. MSc thesis, Wageningen University, Netherlands.

KRONER, C. & T. JAHR (2006): Hydrological experiments around the superconducting gravimeter at Moxa observatory. J of Geodynamics, vol 41, Issues 1–3, 269–275.

KRONER, C., T. JAHR, M. NAUJOKS, A. WEISE (2007): Hydrological signals in gravity – foe or friend? International association of Geodesy symposia, 2007, vol. 130, part IV, 504–510.

LYON, S.W. & P.A. TROCH (2007): Hillslope subsurface flow similarity: real-world tests of the hillslope Péclet number. Water Resources Research, vol 43.

NAUJOKS, M., C. KRONER, A. WEISE, T. JAHR, P. KRAUSE, E. EISNER (2010): Evaluating local hydrological modelling by temporal gravity observations and gravimetric three-dimensional model. Geophysical Journal International, vol 182, 233–249.

NIESSEN, S.E.W. & C.M. WESSELIUS (2005): Groundwater flow and storage distribution in vicinity of the Geodynamic observatory Moxa, Germany. Fieldwork and hydrological modelling. Master thesis Wageningen University, Netherlands.

PANICONI, C., P.A. TROCH, E.E. VAN LOON, A.G.J. HILBERTS (2003): Hillslope-storage Boussinesq model for subsurface flow and variable source areas along complex hillslopes. Intercomparison with a three-dimensional Richards equation model. Water Resources Research, vol 39, no 11, 1317.

THÜRINGER LANDVERMESSUNGSAMT (1999): Topographische Karte 1:25000, Normalausgabe 5335

VERMUE, E. & T. VAN DE VOORDE (2005): Characterization of flow patterns in the Silberleite catchment. Fieldwork and explorational modeling to link hydrology to gravity. MSc thesis, Wageningen University, Netherlands.

Address of authors

R. Dijksma, H.A.J. van Lanen, G. Bier, Wageningen University, the Netherlands.
T. Jahr, Institute of Geosciences, Friedrich Schiller University Jena, Germany.

Corresponding author
Roel Dijksma, roel.dijksma@wur.nl