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Method for spatially distributed modelling of evapotranspiration and fast runoff components to describe large-scale groundwater recharge

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Abstract A method for the determination of spatially distributed long-term mean groundwater recharge from precipitation in macroscale (several thousand km^2) study areas is described. An evapotranspiration model to simulate long-term total runoff is combined with a regionalized long-term separation into fast runoff components and baseflow to account for runoff generation in mountainous regions. The first part of this contribution deals with the calibration and validation of the evapotranspiration model at 21 lysimeters. The second part deals with the development and testing of a regionalization model on 105 catchments, using multiple linear regression. It estimates the baseflow/total runoff ratio from physiographic catchment characteristics, which are important for runoff generation, for small catchments with a satisfying accuracy.

Key words baseflow regionalization; evapotranspiration model; groundwater recharge; lysimeters; multiple linear regression

INTRODUCTION

In addition to spatially distributed long-term averages, monthly groundwater recharge is needed as a boundary condition for non-steady groundwater models. One method of modelling groundwater recharge is by establishing a water balance of the active soil layer. Modelling of the processes of evapotranspiration and vertical soil water movement can be done at different levels of complexity (Wegehenkel, 1997). One-dimensional SVAT-models describe the processes in great detail (e.g. Menzel, 1997). Some SVAT-models also account for lateral flow processes, which might influence evapotranspiration locally by a spatial redistribution of subsurface water (e.g. Famiglietti & Wood, 1994).

The separation of runoff components is implemented in existing hydrological models. However, there is a gap between understanding of the process of runoff generation and its conceptualization in hydrological models (Leibundgut *et al.*, 2001). In conceptual rainfall runoff models, e.g. HBV (Bergström, 1992), the runoff component separation depends on parameters calibrated against total runoff. Different parameter sets with comparable goodness in terms of model fit, as well as differences in model structure result in different portions of runoff components (Uhlenbrook *et al.*, 1999). The separation into runoff components is often modelled in a lumped way. In water balance models with physically based soil modules based on Richards' equation, e.g. WASIM ETH (Schulla & Jasper, 1998), the separation into runoff components takes place in soil layers. However, a parameterization based on large-scale digital soil datasets (1:200 000) is problematic. Some SVAT-schemes consider a redistribution of water in the catchment (e.g. Famiglietti & Wood, 1994) by modelling saturated subsurface flow based on the topographic soil index. Total runoff is only separated into saturated overland flow and groundwater flow.

The first part of this contribution presents results of evapotranspiration and groundwater recharge modelling in alluvial aquifers, using a detailed water balance of the active soil layer in an extended version of the one dimensional SVAT-scheme TRAIN (Menzel, 1997). In complex terrain (mountains with underlying bedrock), TRAIN has the potential to model total runoff, which has to be separated into different components in order to obtain groundwater recharge. In view of the limitations of runoff generation conceptualization in existing hydrological models, and the non-detailed input data (1:200 000) at the macroscale, an alternative approach was chosen. The second part of this contribution deals with the regionalization of the long-term ratio of baseflow/total runoff. The resulting model describes the component separation spatially distributed on the basis of small catchments in dependence on relevant physiographic catchment characteristics.

MODEL DESCRIPTION

Groundwater recharge from precipitation (*GWR*) is determined by the water balance equation:

$$GWR = (P - ET) \times \frac{Q_b}{Q_t} \tag{1}$$

Evapotranspiration loss (*ET*), which is determined by a complex SVAT-scheme is subtracted from precipitation (*P*), resulting in total runoff (*P* – *ET*). Further losses by fast flow components are accounted for by multiplying total runoff with the proportion of baseflow at total runoff (Q_b/Q_t), regionalized by a statistical model.

Evapotranspiration model

The SVAT-scheme TRAIN (Menzel, 1997) is run on a daily time-step and needs precipitation, temperature, humidity, wind speed and sunshine duration as input. Processes which are modelled include: radiation calculation, snow accumulation (Schulla & Jasper, 1998) and snowmelt (temperature index method), interception and evaporation of intercepted water (Menzel, 1997), actual transpiration based on the Penman-Monteith relationship, soil water storage/percolation according to the soil model of the HBV rainfall–runoff model (Bergström, 1992), and capillary rise according to Renger *et al.* (1974). The soil model is a conceptual two-parameter model and it predicts water percolation at each time step from water infiltration into the soil (no Horton overland flow is allowed). The percolating water is part of the input water, depending on the actual soil water content, according to the following equation:

$$\frac{\Delta PERC}{\Delta INPUT} = \left(\frac{SWC}{PAW}\right)^{BETA} \tag{2}$$

where $\Delta PERC$ = percolation during the time step, $\Delta INPUT$ = input water from precipitation/snowmelt during the time step, SWC = soil water content, PAW = plant available water in the effective root zone and $BETA$ = model parameter, related to PAW (see below). Percolation out of the soil takes place before the actual soil water content reaches its maximum value (PAW), accounting for macropore flow, and in the case of spatial applications, for soil heterogeneity (Bergström & Graham, 1998).

Separation of baseflow

Runoff components can be defined in different ways. Isotope and geochemical tracers allow conclusions on the sources and pathways of the water (e.g. Bonell, 1998). In contrast to this "process oriented" definition, baseflow in a "dynamic sense" is defined as discharge that is exclusively active during low flow conditions. It is not possible to directly associate baseflow (dynamic sense) to process oriented runoff components. In this study long-term baseflow is determined by a modified Wundt/Kille method (Schreiber, 1996) that is often applied in Germany. Rather than continuous baseflow hydrograph separations, as discussed e.g. in Nathan & McMahon (1990), the long-term baseflow is determined by using the monthly lowest discharges of a 30 year reference period (1961–1990). It is considered to represent mean long-term groundwater recharge.

APPLICATION OF THE SVAT-MODEL AT LYSIMETER SITES

The SVAT-model was applied at 21 different lysimeter sites in the southwest of Germany, in order to relate the soil parameter *BETA* to other available parameters, and to evaluate the performance of the SVAT-scheme in modelling groundwater recharge.

Method and data

The 20 non-weighable lysimeters (+ one weighable lysimeter) differ a lot with respect to soil depth and substrate (sand to silt), land use (grassland, agriculture), altitude (105–560 m a.m.s.l.), and climatic conditions (mean annual precipitation P: 650–1000 mm). The available model input data from the lysimeter sites is relatively non-detailed, comparable to datasets of macroscale spatial applications (soil depth, predominant texture, land use (grassland or agriculture), precipitation at the lysimeter site and meteorological data from the closest official weather station). Due to its physical basis, the parameters of the evapotranspiration model are fixed, except for *BETA*, from the conceptual soil module. The second soil parameter *PAW* is determined on the basis of the mean effective root depth of the land use and the substrate (AG Boden, 1994). In a first step the empirical parameter *BETA* is calibrated on measured percolation (aggregated to four-week totals) of a four-year calibration period from April 1987 to March 1991 (goodness of fit: relative difference of the whole period (rd) and the Nash-Sutcliffe model efficiency (R_{eff})). Groundwater recharge is assumed to be percolation with a certain time lag. An estimation function for *BETA* is derived. In a second step, the lysimeter is modelled for the same period, with the estimated *BETA* and the results are evaluated (Armbruster *et al.*, 2000). The model is also validated on evapotranspiration data from a weighable lysimeter over a two-year period from January 1995 to December 1997. Only rainless days are chosen to minimize errors in the determination of evapotranspiration from weight measurements.

Results

The optimized *BETA* ranges within the whole pre-set range from 1 to 7. Uhlenbrook, *et al* (1999) gives a range from 1 to 5. *BETA* increases with increasing *PAW* at the lysimeter site (Fig. 1). An estimation function for *BETA* that is dependent on PAW is derived. The percolation modelling of the 20 lysimeter sites with the estimated *BETA* resulted in a mean of the relative difference of 1.3% (between –14% and +24%; values for 10 lysimeters were between –5% and +5%), indicating no considerable systematic under/overestimation, and as a mean there is an under/overestimation of 8.5%. The mean model efficiency is 0.72 (0.36–0.92). This is remarkable, considering the non-detailed input data and the fact that no extensive calibration was conducted.

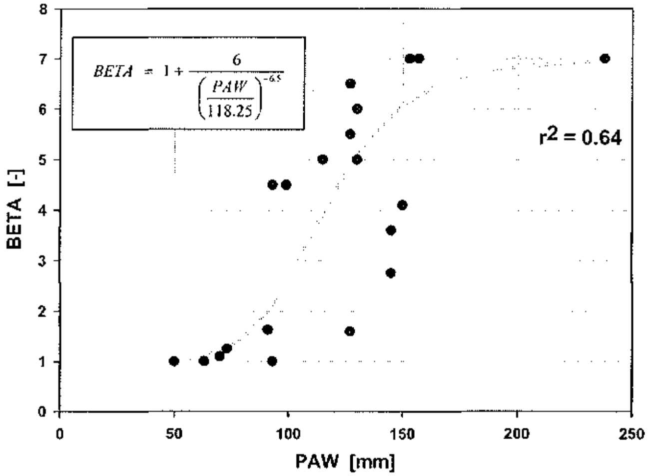

Fig. 1 The dependence of *BETA* on *PAW* (estimation function of *BETA*).

Groundwater recharge time series at two lysimeters show the range of the results (Fig. 2). One of the best results (R_{eff}: 0.92, *rd*: +7%) was obtained at site A (agriculture, very deep silt soil, *P*: 870 mm), one of the worst modelling results (R_{eff}: 0.41, *rd*: +24%) was obtained at site B (agriculture, 0.5 m deep loam soil, *P*: 630 mm). During major recharge periods, peaks are slightly overestimated and at their end, the recharge is slightly underestimated, suggesting that the conceptual soil model does not describe retention and drainage of water from the soil exactly.

The model was further validated on daily evapotranspiration at the weighable lysimeter (grassland, 0.5 m deep loam soil, *P*: 880 mm, Fig. 3). Slight model underestimation of high values and slight overestimation of low values can be observed. The linear regression of the scatter plot has an R^2 of 0.87. The cumulative sum of evapotranspiration, determined from weight measurements, is 619 mm; the modelled one is 4% less.

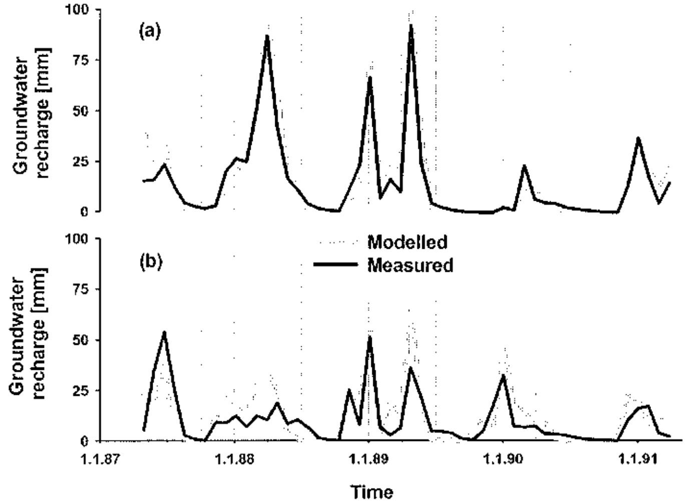

Fig. 2 Modelled and measured time series of groundwater recharge (four-week totals) of (a) one of the best modelling results and (b) one of the worst modelling results.

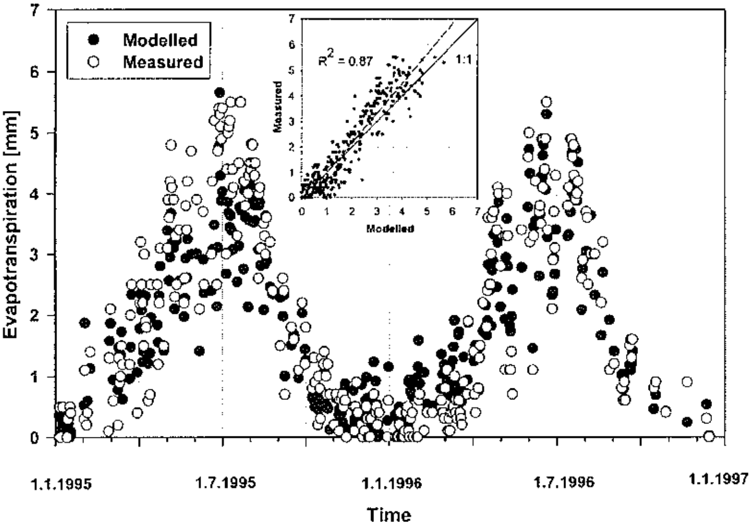

Fig. 3 Observed (determined from weight measurements) and modelled daily evapotranspiration for days without rain in 1995 and 1996 at the weighable lysimeter.

The evapotranspiration model has been tested based on relatively non-detailed input data sets at the lysimeter sites, comparable to available macro-scale datasets. It proved suitable to describe percolation (groundwater recharge) from precipitation on a monthly basis for alluvial aquifers. Although the results are obtained at the point scale, it seems justified to use them at larger scales. In areas with thin soils (low values of *PAW*) the soil heterogeneity affects percolation more strongly. This is reflected by lower *BETA* values, accounting for this effect. The low soil data requirements (only *PAW* has to be derived) are important for large-scale applications.

DEVELOPMENT OF A STATISTICAL MODEL TO ESTIMATE Q_b/Q_t

Method and data

The multiple linear regression method is used for the regionalization. Within the study area (the State of Baden-Württemberg in southwest Germany, 35 000 km^2), catchments with significant fast runoff generation processes (mountainous with only minor alluvial aquifers) and daily discharge data for the reference period, 1961–1990, were selected. The 105 catchments range in size between 7 and 400 km^2. For the catchments the ratio Q_b/Q_t and relevant catchment characteristics (e.g. soil conductivity, slope, precipitation etc.), were determined based on knowledge of runoff generation processes at the microscale. The data was split into a set for calibration (n = 70) to develop the model and one for validation (n = 35).

Results

The ratio Q_b/Q_t is not very variable during the time period (as shown by different 5-year periods within the 30-year period), indicating that it represents a stable, long-term catchment characteristic. The parameters used to predict the ratio are also not temporally variable. They mainly describe soils, hydrogeology, and topography. This suggests the possibility of applying the ratio on a shorter time scale (a few years). A significant difference from other baseflow regionalization studies using the multiple linear regression method (Schreiber, 1996), is that Q_b/Q_t shows no correlation with catchment size. In other words, it is independent of spatial scale. The ratio ranges from 0.15 to 0.79, while 40% of the values are between 0.3 and 0.4.

The multiple linear regression resulted in the following model (other models with comparable accuracy could be derived):

$$\begin{aligned}\frac{Q_b}{Q_t} &= 0.55 + 0.5 \times PAW_{high} - 0.18 \times soilin_{low} - 0.15 \times DD + 417.99 \times hgcon_{mean} \\ &\quad + 0.12 \times A_{low} + 0.19 \times hgcon_{high} - 0.2 \times karst - 0.12 \times soilcon_{low} \\ &\quad - 0.13 \times soilret_{low} + 0.37 \times soilin_{high}\end{aligned} \tag{3}$$

where Q_b/Q_t = estimated ratio, PAW_{high} = fraction of soils with high plant available water in the effective root zone (>200 mm), $soilin_{low}$ = fraction of low infiltrating soils over low permeable bedrock, DD = drainage density, $hgcon_{mean}$ = mean conductivity of hydrogeological units, A_{low} = fraction of altitudes between 300 and 450 m a.m.s.l., between $hgcon_{high}$ = fraction of hard rock hydrogeological units with high conductivity (>10^{-5} m s^{-1}), $karst$ = fraction of karstified areas, $soilcon_{low}$ = fraction of soils with low vertical conductivity (<10 cm day^{-1}), $soilret_{low}$ = fraction of soils with low retention capacity and $soilin_{high}$ = fraction of high infiltrating soils.

The model satisfies the statistical requirements (no overfitting, model significance, significance of predictor variables, no colinearity between predictor variables, residuals are approximately normally distributed) and yields an R^2 of 0.75 for the calibration data set and an R^2 of 0.66 for the independent validation dataset. All predictors can be interpreted well in terms of runoff generation. The model has the capacity to estimate Q_b/Q_t spatially distributed on the basis of small catchments in areas with lateral flow components, independently of discharge data.

CONCLUSIONS

The approach of combining long-term total runoff, calculated by a SVAT-model on daily time steps, with an empirical long-term runoff component separation, is an alternative to existing hydrological models describing groundwater recharge. In areas without fast flow components, groundwater recharge is modelled exclusively by the SVAT-scheme, while in mountainous areas it is complemented by the component separation. The component separation used has the advantage that it is based on many different catchment characteristics which are well known to be relevant for runoff generation. However, it does not describe the inter-annual or event-based variation of component contributions. The component separation could be regionalized, as it is based on widely available discharge data. This implies that the method separates components in a dynamic sense. Future work will focus on the application of this approach to the state of Baden-Württemberg (35 000 km^2) to determine spatially distributed groundwater recharge. Total runoff will be determined on a 500 × 500 m grid basis and combined where necessary with a component separation spatially distributed on the basis of small catchments.

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REFERENCES

AG Boden (1994) *Bodenkundliche Kartieranleitung* (Soil mapping guide). Schweizerbart, Stuttgart, Germany.

Armbruster, V., Leibundgut, Ch. & Menzel, L. (2000) Modellierung der detaillierten Grundwasserneubildung im Lockergestein mit einem SVAT-Modell (Modelling detailed groundwater recharge of alluvial aquifers by a SVAT-model). *Wasser & Boden* **11**, 24–28.

Bergström, S. (1992) The HBV model: its structure and applications. *SMHI, RH 4, Norrköping, Sweden.*

Bergström, S. & Graham, L. P. (1998) On the scale problem in hydrological modelling. *J. Hydrol.* **211**, 253–265.

Bonell, M. (1998) Selected challenges in runoff generation research in forests from the hillslope to headwater drainage basin scale. *J. Am. Wat. Resour. Assoc.* **34**(4), 765–785.

Famiglietti, J. S. & Wood, E. F. (1994) Multiscale modelling of spatially variable water and energy balance processes. *Wat. Resour. Res.* **30**(11), 3061–3078.

Leibundgut, Ch., Uhlenbrook, S. & McDonnell, J. J. (eds) (2001) *Runoff Generation and Implications for River Basin Modelling.* (Proc. Freiburg Workshop, October 2000). Freiburger Schriften zur Hydrologie, Band 13, Freiburg, Germany.

Menzel, L. (1997) *Modellierung der Evapotranspiration im System Boden-Pflanze-Atmosphäre* (Modelling evapotranspiration in the soil–vegetation–atmosphere system). Zürcher Geographische Schriften 67, Zürich, Switzerland.

Nathan, R. J. & McMahon, T. A. (1990) Evaluation of automated techniques for base flow and recession analysis. *Wat. Resour. Res.* 7(26), 1465–1473.

Renger, M., Strebel, O. & Giesel, W. (1974) Beurteilung bodenkundlicher, kulturtechnischer und hydrologischer Fragen mit Hilfe von klimatischer Wasserbilanz und bodenphysikalischen Kennwerten (Evaluation of soil scientific and hydrological questions, based on climatic water balance and soil physical properties). *Z. Kulturtechnik und Flurbereinigung* 15(1/2) Bericht, 148–160, 206–221.

Schreiber, P. (1996) *Regionalisierung des Niedrigwassers mit statistischen Verfahren* (Regionalization of low flow with statistical methods). Freiburger Schriften zur Hydrologie, Band 4, Freiburg, Germany.

Schulla, J. & Jasper, K. (1998) *Modellbeschreibung WaSiM-ETH* (Model description WaSiM-ETH). ETH-Zürich, Switzerland.

Uhlenbrook, S., Seibert, J., Leibundgut, Ch. & Rodhe, A. (1999) Prediction uncertainty of conceptual rainfall–runoff models caused by problems in identifying model parameters and structure. *Hydrol. Sci. J.* 44(5), 779–797.

Wegehenkel, M. (1997) A modular modelling system for calculating evapotranspiration, soil water dynamics and groundwater recharge under various land-use systems. In: *Ecohydrological Processes in Small Basins* (ed. by D. Viville & I. G. Littlewood) (Proc. Strasbourg Conf., September 1996), 43–49. IHP Tech. Doc. no. 14, UNESCO, Paris, France.