Models – Repositories of Knowledge
(Proceedings ModelCARE2011 held at Leipzig, Germany, in September 2011) (IAHS Publ. 355, 2012).

Generating land-use information to derive diffuse water and nitrate transfer at aquifer scale

GERNOT KLAMMLER, GERHARD ROCK, HANS KUPFERSBERGER & JOHANN FANK

JOANNEUM RESEARCH Forschungsgesellschaft Graz, RESOURCES – Institute of Water, Energy and Sustainability, Elisabethstraße 16/II, Water Resources Management, A-8010 Graz, Austria

gernot.klammler@joanneum.at

Abstract Modelling diffuse water and nitrate transfer in the unsaturated zone is a state-of-the-art method for determining groundwater recharge and nitrogen leaching at aquifer scale, which can be used to define the upper boundary condition for transient groundwater flow and transport models. Together with soil and weather data, land-use information is an indispensable input parameter for modelling groundwater recharge and nitrogen leaching, but is not available in detail at aquifer scale. In Austria, information concerning cultivated crops is only available as annual crop percentages on the aggregated level of cadastral municipalities. To deal with this problem a stochastic crop rotation tool *StotraPGen* is developed which uses multiple crop rotations and derives optimal percentages of characteristic crop rotations for representing the statistical land-use data. To validate the approach of *StotraPGen* the agricultural research site Wagna (Austria) is treated as a single cadastral municipality. Based on the exact land-use knowledge, annual crop percentages (as it is available at aquifer scale) are computed for the period 1988–2009. In a next step, the time series of groundwater recharge and nitrate leaching are simulated using (a) the actually applied crops and fertilizers, (b) the stochastic land-use approach *StotraPGen* and (c) using just one single crop rotation. The comparison of the results shows that *StotraPGen* very closely resembles the simulated unsaturated zone response due to the real agricultural land-use. Using one single crop rotation does not yield satisfying groundwater recharge and nitrogen leaching results on a daily basis. Future work will focus on upscaling uncertainties due to insufficient soil depth information at aquifer scale, and iterative coupling between saturated and unsaturated water flow and solute transport models to improve the representation of the saturated–unsaturated interface in future model simulations.

Key words vadose/unsaturated zone; diffuse water and nitrate transfer; groundwater recharge; nitrate/nitrogen leaching; land-use; modelling; aquifer/regional scale, multiple crop rotation

INTRODUCTION

A wide range of different factors influences the quantity and quality of groundwater. In particular, application of nitrogen fertilizer in agriculturally used areas can lead to a significant threat for shallow aquifers. To guarantee drinking water supply and to protect groundwater dependent ecosystems, groundwater resources must be managed in a sustainable way. In the Groundwater Directive (GWD, 2006), maximum limits of pollutant concentrations have been set for nitrate (50 mg L^{-1}) and other pollutants in groundwater bodies. The legislation intends to safeguard groundwater resources while maintaining important land-uses such as agriculture, forestry, urban development and industry. To comply with these threshold values in agriculturally-used areas, management strategies (e.g. amount of fertilizer, date of fertilization) for endangered regions like the Murtal aquifer (Styria, Austria) have to be adapted (Fank *et al.*, 2010). According to Lerner & Harris (2009) “current land-use instruments have only been designed to address quality issues in groundwater and do not consider recharge and these instruments have been largely ineffective in protecting groundwater from diffuse pollution”. In any case, a nitrate concentration in seepage water underneath the root zone below 50 mg L^{-1} provides for a “good environmental status” of the groundwater quality concerning nitrate in the long run. Dilution from surface waters or artificial groundwater recharge additionally enhances water quality in terms of nitrogen content in certain cases.

Environmental, economic and political decisions for safeguarding future co-existence between agriculture and drinking water supply are commonly based on decision support systems like saturated and unsaturated water flux and transport models. These models try to describe hydrological processes in the vadose zone for a certain period of time including soil and plant processes under different weather conditions. At aquifer scale information concerning land-use, soil and weather is not always available in adequate quantity and quality. Thus, this paper deals with upscaling uncertainties due to insufficient land-use information.

Depending on the land-use distribution within the investigation area and the desired accuracy of results, different emphases are set on spatial and temporal input data resolution for the purpose of modelling unsaturated water flux and solute transport. While some applications only distinguish between general land-use classifications like urban areas, forests, agriculture etc. (Santhi *et al.*, 2006; Zagana *et al.*, 2007; Tesch *et al.*, 2010), Almasri & Kaluarachchi (2007) and Sohier *et al.* (2009) also differentiate between certain crops within the agricultural land-use type, while a temporal change of crops is not considered. In agricultural practice the crop rotation (combination and sequence of crops) plays a central role in farming systems and affects crop yields, soil erosion, pests, diseases, weeds and dynamics of nitrogen (Dogliotti *et al.*, 2003). Hence, modelling the temporal variability of groundwater recharge and nitrate leaching of arable land also requires the consideration of cultivated crop sequences.

Simple approaches (e.g. Akhavan *et al.*, 2010) only consider one typical crop rotation representative for the entire investigation area. Since different crops influence groundwater recharge and nitrogen leaching in different forms (Klammler *et al.*, 2011) and, generally, more than one single crop is cultivated in a certain year, Klöcking *et al.* (2003) describe a more complex approach to handle such input data scenarios. Based on the spatial crop distribution within the investigation area, a 40-year virtual crop sequence is generated, i.e. the frequency of one crop in this virtual crop rotation represents its spatial appearance (e.g. 10% winter wheat is represented by four times winter wheat in 40 years). To address the spatial distribution within single years, the whole arable land is divided into 40 classes (minimum raster cell size 4 ha), each representing a different starting element of the virtual crop rotation in the first year of the simulation. Even though only one crop per year is considered within one of the 40 classes, Klöcking *et al.* (2003) involve the spatial and temporal distribution of crops in hydrological modelling.

To minimize uncertainties concerning land-use input, the present approach *StotraPGen,* a pre- and post-processing tool for modelling unsaturated soil water flux and nitrogen transport at aquifer scale, was developed for arable land where crop rotations are applied. *StotraPGen* partly shares basic ideas with Klöcking *et al.* (2003) (e.g. different starting elements of the same crop rotation), but is also able to consider multiple crop rotations, which are shorter and therefore more realistic. Furthermore, in contrast to gaining land-use input from remote sensing data (Montzka *et al.*, 2008a,b), *StotraPGen* uses crop distribution data available at aquifer scale from the IACS-database (Integrated Administrative and Control System of the European Union). Moreover, *StotraPGen* enables changes to be simulated in cultivation schemes (e.g. reductions of fertilizer amounts due to designation of protection areas) or changes in spatial crop distribution over time. The objective of this paper is to describe and to validate the *StotraPGen*-approach.

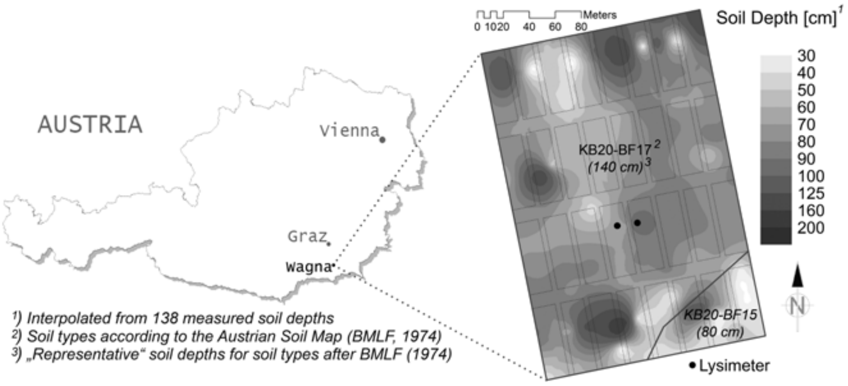
METHODS

Data

The test site Wagna with a total area of 4.4 ha is located within the unconfined aquifer Westliches Leibnitzer Feld (approx. 45 km^2) about 30 km south of Graz (Fig. 1). It is situated on a gravel terrace of Würm glaciation, which is covered with clayey-sandy Cambisols. As evident from Fig. 1, soil depths within the test site are very heterogeneous and range between 20 and >200 cm. The test site consists of 32 lots (1000 m^2 each) where different fertilizer schemes and crop rotation patterns have been tested since 1988. Information like cultivated crops, dates of sowing/harvesting/fertilization/tillage and applied amounts of fertilizer are recorded. Weather data are acquired at a weather station of the national meteorological service (ZAMG) which is situated at the test site. In 2004 two lots were equipped with weighable monolithic equilibrium suction field lysimeters and an accompanying soil hydrologic measuring profile (Fank & v. Unold, 2007).

Model

The unsaturated, 1-D, vertical soil water and nitrogen transport model SIMWSER/STOTRASIM is developed for modelling groundwater recharge and nitrate leaching of arable land. While



1) Interpolated from 138 measured soil depths
2) Soil types according to the Austrian Soil Map (BMLF, 1974)
3) „Representative" soil depths for soil types after BMLF (1974)

Fig. 1 Location, soil depths and soil types of the agricultural test site Wagna (Styria, Austria).

SIMWASER (Stenitzer, 1988) calculates water flux based on the Darcy-Buckingham equation and the condition of continuity, STOTRASIM (Feichtinger, 1998) simulates nitrogen dynamics in the soil and nitrogen leaching into the groundwater on daily time steps. The model is calibrated against soil water and nitrogen fluxes measured at the Wagna lysimeters for the period 2004–2009.

Validation approach

In Austria, agricultural land-use information (i.e. cultivated crops) at the aquifer scale is only available as aggregated percentages for cadastral municipalities. In this study the approaches *Single Crop Rotation* (Akhavan *et al.*, 2010) and *StotraPGen* are validated by the *Real Crop Rotations* at the agricultural research site Wagna, which is treated as a single cadastral municipality, i.e. based on the exact land-use knowledge in Wagna, annual crop percentages are computed (as it is available in Austria at aquifer scale) and land-use input data for the *Single Crop Rotation* and for *StotraPGen* are derived. Modelling results are then compared to the groundwater recharge and nitrogen leaching of the *Real Crop Rotations*, which serves as reference.

Crop rotation approaches

The *Real Crop Rotations* contain 33 different crop rotations (32 lots and the grassland area between the lots) where the exact cultivation is known from 1988 until present.

The *Single Crop Rotation* is one single sequence of crops, which represents the spatial crop distribution of an area, e.g. 40% maize, 20% oil pumpkin, 20% winter barley and 20% winter rape in the investigation area can be represented by the 5-year (100 / 20 = 5) crop rotation *maize - oil pumpkin – maize – winter barley – winter rape*, but also by all other variants of these four crops (unless specific sequences are agriculturally not practicable). Hence this method is strongly dependent on user-based definitions of the crop sequence. Furthermore, it considers only one crop in one year and therefore the unsaturated water flux and nitrogen transport in that year is strongly affected by the simulated crop. In this paper, only crops with >7% area are considered and thus the *Single Crop Rotation* consists of 14 elements (100 / 7 = 14) which are expanded to the simulation period (using default dates for sowing/harvesting/fertilization/tillage). To include the randomness of the user's definition of which crop starts the crop rotation, the defined sequence of *Single Crop rotation* is simulated 14 times, each time starting with another element in the sequence (i.e. after the first simulation run the next sequence is started with element 2, element 1 is put backwards behind element 14).

StotraPGen is a pre- and post-processing software tool for SIMWASER/STOTRASIM that derives optimal percentages of several characteristic crop rotations for representing the statistical land-use data. It performs the following steps (see also the example in Table 1):

(a) Defining one or more crop rotations by user (default dates for sowing/harvesting/fertilization/tillage), which are actually cultivated in the investigation area (by means of agricultural expert knowledge; Roman numerals in Table 1(a)).
(b) The user can define if one crop rotation is representative for the entire modelling period or just for sub-periods (Table 1(b)).

(c) *StotraPGen* generates all possible variants (V1 to V4 in Table 1 (c)) of the defined crop rotations by putting the last crop of the original crop rotation in front (the indexes in Table 1 (c) indicate the temporal displacement of the crops). So several different crops are considered in one year (upright letters in Table 1(c)).
(d) *StotraPGen* expands the variants of crop rotations for the defined modelling period or sub-periods automatically (italics in Table 1(c)).
(e) *StotraPGen* calculates by an optimization algorithm the optimal percentage of every variant of crop rotation for representing the statistical land-use data.
(f) *StotraPGen* mixes the simulation results of every variant of crop rotation based on the optimal percentage for every hydrologic response unit (HRU).

Table 1 Procedure for generating land-use information with *StotraPGen* (example).

(a)		(b)		(c)																
Crop rotations		Sub-Periods		I					II					III						IV
				88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	…
I	M-M-WW-WR[a]	88–92	V1:	M$_1$	M$_2$	WW$_3$	WR$_4$	*M*$_1$	M$_1$	M$_2$	WB$_3$	WR$_4$	*M*$_1$	M$_1$	WB$_2$	OP$_3$	M$_4$	*M*$_1$	*WB*$_2$	
II	M-M-WB-WR[a]	93–97	V2:	WR$_4$	M$_1$	M$_2$	WW$_3$	*WR*$_4$	WR	M	M	WB	*WR*	M	M	WB	OP	*M*	*M*	…
III	M-WB-OP-M[b]	98–03	V3:	WW$_3$	WR$_4$	M$_1$	M$_2$	*WW*$_3$	WB	WR	M	M	*WB*	OP	M	M	WB	*OP*	*M*	
IV	M-WB-OP-M[c]	04–09	V4:	M$_2$	WW$_3$	WR$_4$	M$_1$	*M*$_2$	M	WB	WR	M	*M*	WB	OP	M	M	*WB*	*OP*	

M, Maize; WW, Winter Wheat; WR, Winter Rape; OP, Oil Pumpkin.
(a) without winter catch crop; (b) with winter catch crop; (c) like (b), but different fertilizer amount.

StotraPGen is able to handle any number of soil types, but to skip the influence of soil heterogeneity and to set the focus on uncertainties concerning land-use input, only one representative soil with a mean soil depth of 80 cm is used. The validation period is from 1988 to 2009, where detailed cultivation data is available. Feichtinger (1998) recommends a previous simulation period of at least three years before validation to compensate for uncertainties in the initial conditions, which is considered in this paper.

RESULTS

As can be seen in Table 2, long-term annual average groundwater recharge and nitrogen load using *StotraPGen* or a S*ingle Crop Rotation* do not differ significantly from results of the *Real Crop Rotations.* However, the model results for annual or shorter time steps of the *Single Crop Rotations* vary notably. Table 2 shows the maximum annual error and the Nash-Sutcliffe efficiency NSE on an annual and daily basis. It is obvious that *StotraPGen* leads to more accurate results than the *Single Crop Rotation* approach, especially for the nitrogen leaching, which is illustrated in Fig. 2(a). That fact also results in larger ranges for mean annual nitrate concentrations of the *Single Crop Rotation* approach given in Fig. 2(b) (the generally decreasing trend of nitrate concentrations can be attributed to the applied fertilization scheme).

Table 2 Long-term annual average of groundwater recharge (GWRC) and nitrogen load from 1988 to 2009.

	Single Crop Rotations	*StotraPGen*	*Real Crop Rotations*
GWRC (mm a^{-1})	291 – 304*	295	293
N-Load (kg ha^{-1} a^{-1})	17 – 22*	19	19

Table 3 Max. annual error and Nash-Sutcliffe efficiency (annual and daily basis) for GWRC and N-Load.

	Groundwater Recharge			*Nitrogen Load*		
	Max. Error	NSE$_{annual}$	NSE$_{daily}$	Max. Error	NSE$_{annual}$	NSE$_{daily}$
StotraPGen	22 mm a^{-1}	0.996	0.991	8 kg ha^{-1} a^{-1}	0.901	0.946
Single Crop R.	50 mm a^{-1}	0.985–0.992*	0.948–0.964*	42 kg ha^{-1} a^{-1}	0.516–0.875*	0.606–0.769*

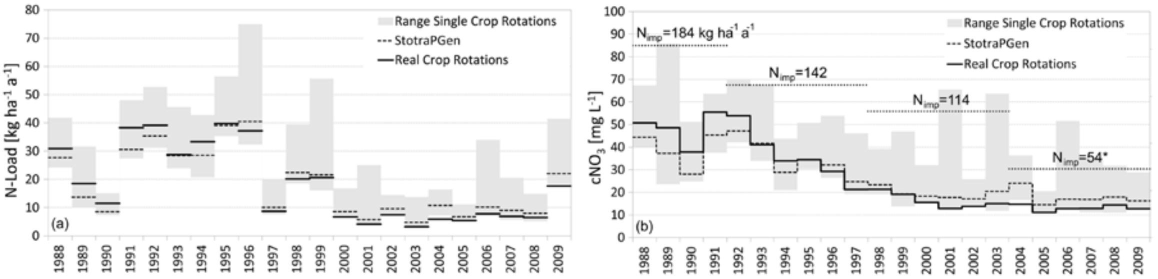


Fig. 2 (a) Annual totals of leached nitrogen loads. (b) Annual means of nitrate concentrations and applied nitrogen amounts (N_{imp}) in kg ha^{-1} a^{-1} due to fertilization (* since 2004 50% of the test site is cultivated by organic farming with no fertilization but high percentages of legumes; N_{imp} due to legumes not included).

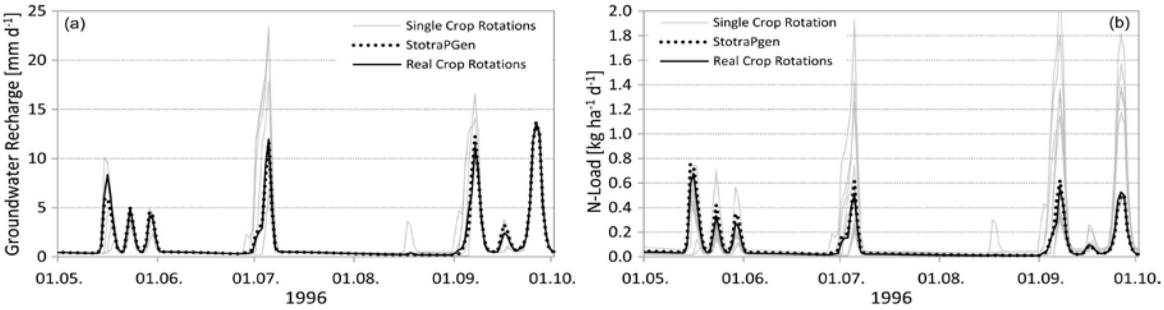


Fig. 3 Daily groundwater recharge (a) and nitrogen leaching (b) for a five-month period in 1996.

Figure 3 illustrates the daily groundwater recharge and the leached nitrogen for a five-month period in 1996, which represents a year with high groundwater recharge rates (approx. 550 mm a^{-1}) and high nitrogen loads (approx. 37 kg ha^{-1} a^{-1}). It can be seen that even for daily sums *StotraPGen* is almost identical to the *Real Crop*, while the *Single Crop Rotations* differ significantly.

DISCUSSION AND CONCLUSIONS

In this paper modelling results serve as reference for assessing the *Single Crop Rotation* and the *StotraPGen* methods assuming that the *Real Crop Rotations* represent reality. By setting the focus on upscaling uncertainties due to insufficient land-use data on aquifer scale, the results show that for daily, monthly and annual bases *StotraPGen* leads to better results of groundwater recharge and nitrate leaching than *Single Crop Rotation* (Akhavan *et al.*, 2010). For long-term annual averages both methods are satisfying, but for annual or shorter time steps results are strongly affected by actually cultivated crops. Since the *Single Crop Rotation* only considers one crop per year and the sequence and starting crop of the *Single Crop Rotation* is defined by a user, there is a high variability between model results. *StotraPGen* eliminates this user-defined randomness by mixing all possible variants of crop rotations. Even though there are deviations between *StotraPGen* and the *Real Crop Rotations*, which result from different field management (fertilizer amounts fluctuate and dates of sowing/harvesting/fertilization/tillage change in reality), upscaling uncertainties caused by land-use distribution can be minimized with *StotraPGen* for simulating groundwater recharge and nitrogen leaching at aquifer scale.

Generating land-use input using remote sensing (Montzka *et al.*, 2008a, b) on the one hand will provide for more accurate spatial land-use information, but on the other hand will also lead to higher costs, since remote sensing data has to be acquired and analysed for the entire investigation area and every single year in the modelling period. Furthermore, *StotraPGen* is easily applicable to other investigation areas without further analysing remote sensing data, which also conforms to the conclusions of Klöcking *et al.* (2003). Hence, *StotraPGen* is a time and cost effective tool to better implement available land-use information for modelling at aquifer scale.

Since the impacts of climate change might affect conditions for agriculture in multiple ways, modelling future scenarios acting as decision support systems are in great demand. In this regard, the advantage of *StotraPGen* is that it is not dependent on the knowledge of the exact crop sequence of every single field in the investigation area, because several possible sequences of crop rotations are considered within a HRU. Klöcking *et al.* (2003) also describes their method as applicable for *scenario development without limitations*.

StotraPGen improves the implementation of land-use information in modelling unsaturated soil water and nitrogen transport at aquifer scale and thus leads to an enhancement of simulation results. This is also an important advantage regarding coupling saturated and unsaturated water flow and transport models to improve the representation of the saturated–unsaturated interface in future modelling approaches. Furthermore, future work will also focus on upscaling uncertainties due to insufficient soil depth information.

Acknowledgement The work was carried out as part of the GENESIS project on groundwater systems (http:/www.thegenesisproject.eu) financed by the European Commission 7FP contract 226536.

REFERENCES

Akhavan, S., Abedi-Koupai, J., Mousavi, S.-F., Afyuni, M., Eslamian, S.-S., & Abbaspour, K. C. (2010) Application of SWAT model to investigate nitrate leaching in Hamadan – Bahar Watershed, Iran. *Agr. Ecosyst. Environ.* 139(4), 675–688.

Almasri, M. N. & Kaluarachchi, J. J. (2007) Modelling nitrate contamination of groundwater in agricultural watersheds. *J. Hydrol*. 343(3–4), 211–229.

BMLF (1974) Österreichische Bodenkartierung. *Erläuterungen zur Bodenkarte 1:25.000 – Kartierungsbereich Leibnitz (Steiermark).* Bundesministerium für Land- und Forstwirtschaft, 232, Wien.

Dogliotti, S., Rossing, W. A. H. & van Ittersum, M. K. (2003) ROTAT, a tool for systematically generating crop rotations. *Eur. J. Agron*. 19(2), 239–250.

Fank, J., Dersch, G., Feichtinger, F. & Robier, J. (2010) Erforderliche Maßnahmen und Umsetzungsoptionen für eine grundwasserverträgliche Landwirtschaft im Murtal-Grundwasserleiter. *Bericht zum 2. Umweltökologischen Symposium 2010: Boden- und Gewässerschutz in der Landwirtschaft.* Lehr- und Forschungszentrum für Landwirtschaft Raumberg-Gumpenstein, Irdning, ISBN 978-3-902559-41-8, 43–50.

Fank, J. & v. Unold, G. (2007) High-precision weighable field Lysimeter – a tool to measure water and solute balance parameters. *Int. Water & Irrigation* 27(3), 28–32.

Feichtinger, F. (1998) STOTRASIM – Ein Modell zur Simulation der Stickstoffdynamik in der ungesättigten Zone eines Ackerstandortes. In: *Modelle für die gesättigte und ungesättigte Bodenzone.* Schriftenreihe des Bundesamtes für Wasserwirtschaft, **7**, 14–41, Wien.

GWD (2006): Directive 2006/118/EC of the European Parliament and of the Council of 12 December 2006 on the protection of groundwater against pollution and deterioration. *Official Journal of the European Union*, http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2006:372:0019:0031:EN:PDF (accessed 31 August 2009).

Klammler, G., Draxler, J. C., Fank, J., Kupfersberger, H. & Rock, G. (2011) Optimierung der Landnutzungsinformation als Input-Parameter für die Bodenwasserhaushalts- und Stofftransportmodellierung. *Bericht zur 14. Gumpensteiner Lysimetertagung 2011: Lysimeter in der Klimaforschung und Wasserwirtschaft.* Lehr- und Forschungszentrum für Landwirtschaft Raumberg-Gumpenstein, Irdning. ISBN 978-3-902559-61-6, 127–135.

Klöcking, B., Ströbl, B., Knoblauch, S., Maier, U., Pfützner, B. & Gericke, A. (2003) Development and allocation of land-use scenarios in agriculture for hydrological impact studies. *Phys. Chem. Earth* 28(33–36), 1311–1321.

Lerner, D. N. & Harris, B. (2009) The relationship between land use and groundwater resources and quality. *Land Use Policy* 26(1), 265–273.

Montzka, C., Canty, M., Kunkel, R., Menz, G., Vereecken, H. & Wendland, F. (2008a) Modelling the water balance of a mesoscale catchment basin using remotely sensed land cover data. *J. Hydrol.* 353(3–4), 322–334.

Montzka, C., Canty, M., Kreins, P., Kunkel, R., Menz, G., Vereecken, H. & Wendland, F. (2008b) Multispectral remotely sensed data in modelling the annual variability of nitrate concentrations in the leachate. *Environ. Modell. Softw.* 23(8), 1070–1081.

Santhi, C., Srinivasan, R., Arnold, J. G. & Williams, J. R. (2006) A modelling approach to evaluate the impacts of water quality management plans implemented in a watershed in Texas. *Environ. Modell. Softw.* 21(8), 1141–1157.

Sohier, C., Degré, A. & Dautrebande, S. (2009) From root zone modelling to regional forecasting of nitrate concentration in recharge flows – The case of the Walloon Region (Belgium). *J. Hydrol.* 369(3–4), 350–359.

Stenitzer, E. (1988) SIMWASER – Ein numerisches Modell zur Simulation des Bodenwasserhaushaltes und des Pflanzenertrages eines Standortes. *Mitt. der Bundesanstalt für Kulturtechnik und Bodenwasserhaushalt* 31, 1–118, Petzenkirchen.

Tesch, S., Dunger, V. & Matschullat, J. (2010) Modelling *Groundwater Recharge of an Urban Area in Germany*. Conference Publications, BALOWIS 2010, Ohrid/Macedonia, http://balwois.com/balwois/administration/full_paper/ffp-1767.pdf, (accessed 11 August 2011).

Zagana, E., Kuells, Ch., Udluft, P. & Constantinou, C. (2007) Methods of groundwater recharge estimation in eastern Mediterranean – a water balance model application in Greece, Cyprus and Jordan. *Hydrol. Processes* 21(18), 2405–2414.