Calibration and Reliability in Groundwater Modelling: From Uncertainty to Decision Making
(Proceedings of ModelCARE'2005, The Hague, The Netherlands, June 2005). IAHS Publ. 304, 2006.

Diffuse loading of surface water from groundwater in areas with shallow groundwater tables: quasi-2-D *vs* 2-D simulation

ELISABETH PETERS & JASPER GRIFFIOEN
Netherlands Institute of Applied Geoscience TNO - National Geological Survey (TNO-NITG), PO Box 80015, NL-3508 TA Utrecht, The Netherlands
lies.peters@tno.nl

Abstract The discharge of water and solutes from groundwater to surface water can be simulated using a quasi two-dimensional (2-D) approach. In this approach, variably saturated flow is simulated in a vertical 1-D column and the discharge to the surface water system is simulated using conceptual relations. To test the quasi-2-D approach of SWAP/ANIMO, the results are compared to the results from a 2-D, variably-saturated flow and transport model: Hydrus-2D. The results show that in the case of stationary flow and/or conservative transport the results of the quasi-2-D approach are comparable to those of Hydrus-2D. For variable flow conditions and reactive transport, the results of the two models differ considerably.

Keywords diffuse pollution; non-point source pollution; quasi-2-D; simulation; vadose zone; water table

INTRODUCTION

Pollution of surface water from nonpoint sources, like NO_3 from agricultural activities, is an important issue, which has received considerable attention recently (e.g. Refsgaard *et al.*, 1999; Schoumans & Silgram, 2003). Simulation and prediction of the load of surface water is a complex issue, which requires simulation of the unsaturated/saturated soil system. In areas with shallow water tables, such as The Netherlands, the correct simulation of the water table fluctuations and the depth of the vadose zone is a prerequisite for correct simulation of the solute transport to the surface water system. Full two-dimensional (2-D) or three-dimensional (3-D) simulation of flow and reactive transport in the unsaturated zone is, however, very costly in terms of CPU time. An efficient approach is to simulate the vadose zone only in 1-D (vertical), since the water flow in the vadose zone is mainly vertical. This approach has been applied in well-known models like DAISY (Hansen *et al.*, 1990) and SWAP (van Dam *et al.*, 1997). For catchment-scale modelling, these models can be coupled to (3-D) saturated flow models. This has been done for example by Refsgaard *et al.* (1999) using DAISY and Mike-SHE, and Schoumans *et al.* (2002) using the Dutch national model STONE. STONE is based on the SWAP model (van Dam *et al.*, 1997) to simulate the water flow, and ANIMO (Kroes & Roelsma, 1998) to simulate nitrogen and phosphate transport. In SWAP, discharge to the local surface water system is simulated using conceptual relations based on the depth of the drains and the water table (quasi-2-D approach), which is a very computationally efficient approach for areas having a dense drainage network.

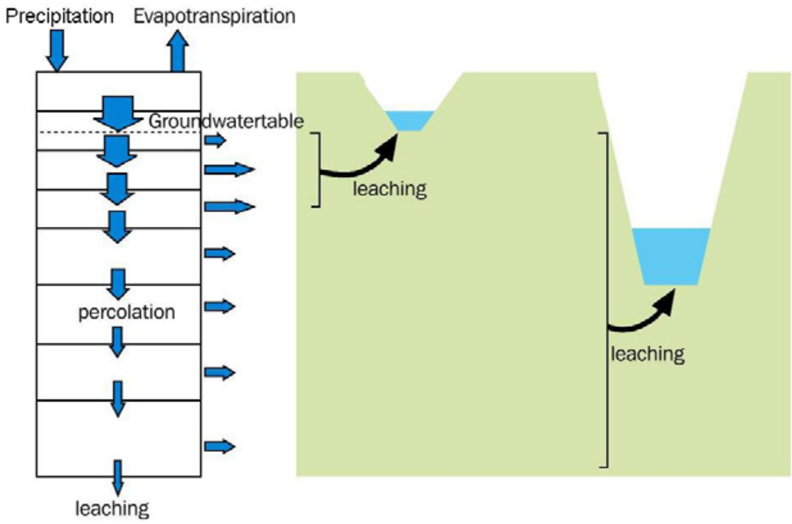

Fig. 1 Illustration of the conceptualization of the water flow in SWAP (adapted from Schoumans & Silgram, 2003).

In the quasi-2-D approach, the flux to the surface water system is simulated using conceptual relations of the form:

$$q = \frac{h_{avg} - h_d}{\gamma} \quad (1)$$

where h_{avg} is the average groundwater level (m), h_d is the drainage level (m) and γ is the drainage resistance (day). h_{avg} is calculated as a weighted average between the groundwater level in the soil column and the drainage level. γ is the sum of the resistance due to flow and the entrance resistance to the drain. The discharge is distributed over the depth of the profile through a linear distribution (Fig. 1).

For water flow, the results of the quasi-2-D approach generally are reliable (van Dam *et al.*, 1997; Groenendijk & van de Eertwegh, 2004). For transport of solutes, however, the results are less certain, especially for non-stationary flow conditions and reactive transport. The purpose of this investigation is to examine the accuracy of the quasi-2-D approach for non-stationary flow conditions by comparing simulations of the quasi-2-D approach in the model SWAP/ANIMO to simulations of the variably-saturated 2-D model Hydrus-2D (Šimůnek *et al.*, 1999). The study was done at the field scale, for two profiles and with cadmium as the model compound. The first profile is a homogeneous sandy profile having a depth of 3.6 m, a drainage distance of 90 m, and drainage depth of 0.95 m. The second is a loamy profile having a depth of 3.6 m and two drainage levels. One drainage level has a drainage distance of 90 m and depth of 0.95 m and the other a drainage distance of 18 m and depth of 0.5 m. In Hydrus-2D, a cross-section of 45 m width is simulated for both soil profiles. In the simulation of drainage in Hydrus-2D only resistance as a result of flow is taken into account. To ensure that the water flow in both models is comparable, the parameter γ in SWAP is calibrated using the results of the Hydrus-2D simulations.

Solute transport for Cd in both models is simulated using the Langmuir adsorption isotherm with a sorption constant of 121 $m^3 g^{-1}$ and maximum adsorption amount of

0.6 mg kg^{-1} in the topsoil (0–20 cm) and 0.15 mg kg^{-1} in the lower part of the profile. The initial solute concentration is a linearly decreasing Cd-concentration in the first top metre of the soil (from 0.025 to 0.0004 μg cm^{-3}). The concentration in the precipitation is 0.0003 μg cm^{-3}. No solute is taken up by the vegetation and the vegetation has a uniform rooting depth of 0.50 m. The identical definition of the geochemical aspects ensures that any differences between the two models can be attributed to the hydrological differences.

RESULTS

Outflow to one drainage level

The quasi-2-D approach generally gives good results for stationary flow conditions and/or conservative tracers (Groenendijk & van de Eertwegh, 2004). To check this, first the model was run with stationary flow conditions and transient flow conditions without adsorption. These scenarios showed only small differences between the results of the SWAP/ANIMO and Hydrus-2D. For the scenario with non-stationary flow conditions and nonlinear adsorption, the differences are considerably larger. The maximum difference in annually averaged concentration (Fig. 2) is almost 60%, and for smaller time steps the differences can be considerably larger. Over the first 30 years, 23% more Cd is discharged according to ANIMO than Hydrus-2D. These differences decrease on longer time scales. There are a number of reasons which can explain (part of) the differences between the results of Hydrus-2D and ANIMO. Some of these are related to specific model characteristics, others to the difference in model concept (quasi-2-D *vs* 2-D).

First, a negative mass balance error exists for Cd in the Hydrus-2D results (2.5% after 30 years), whereas the mass balance errors for ANIMO are very small. However, this error is not large enough to explain the total difference. Second, the retardation is slightly smaller for ANIMO than for Hydrus-2D because of differences in the numerical solution. As a result, the concentration front advances slightly faster in ANIMO and the Cd-concentration in the discharge rises faster in ANIMO. Furthermore, there are some small but consistent differences in the dispersion. These have only limited influence on the Cd-discharge to the stream.

Conceptual differences also play a role. In Hydrus-2D, the discharge concentration is the concentration at the surface water–groundwater interface: the concentration of an infiltrating solute cannot rise before the concentration front is at that interface. The shape of the groundwater table between drains is explicitly taken into account. In SWAP/ANIMO the depth of the groundwater level is a horizontally averaged value for the model area of Hydrus-2D (Fig. 1). This implies that solute load of surface water happens as soon as the average groundwater table lies above the average solute front for an infiltrating solute. Here, the groundwater table is usually more curved than the solute front. This implies that surface load in SWAP/ANIMO happens when the solute front is still above the physical surface water–groundwater interface. Whereas in Hydrus-2D the unsaturated zone is thicker in the immediate vicinity of a drain, and surface load can only happen when the front reaches the interface. This conceptual difference causes the concentration to rise much slower than in ANIMO (Figs 2 and 3(a)).

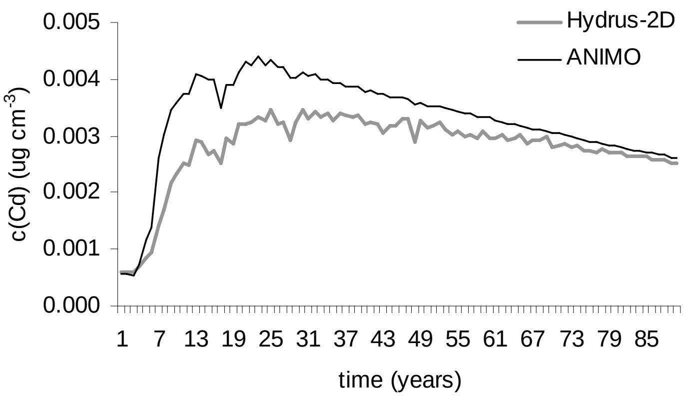

Fig. 2 Annual average Cd-concentration (μg cm^{-3}).

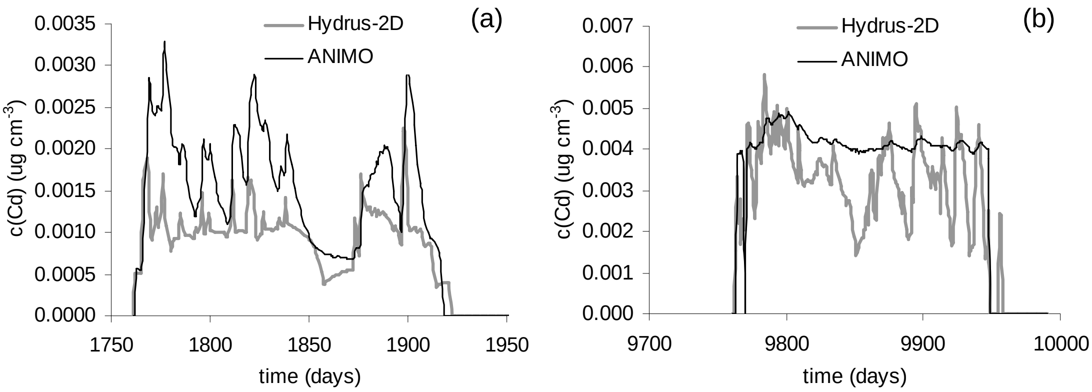

Fig. 3 Examples of the temporal variation in the Cd-concentration in two years of the time series as shown in Fig. 1: (a) winter in the years 5–6, and (b) winter in the years 27–28.

This difference in the concept of the two models also has a strong influence on the temporal variation in the concentration on smaller time scales. In Fig. 3, two examples of the day-to-day variation of the concentration are presented for two years of the time series as shown in Fig. 2. In Fig. 3(a), the fluctuations in the concentration are larger in ANIMO than in Hydrus-2D. For ANIMO, the fluctuations are large, because the concentration front is in the zone of groundwater level fluctuations and model compartments containing Cd-polluted groundwater do not continually contribute to the surface water load (Fig. 4(a)). In Hydrus-2D, the variations are relatively small, because the main part of the pollution has not arrived in the area from which water discharges to the stream. In Fig. 3(b), which is at a later point in the time series, the variations are large for Hydrus-2D and small for ANIMO. For ANIMO, the variations are small because the main part of the pollution is below the zone of water table fluctuations and thus always contributes to the surface water load. For Hydrus-2D, on the other hand, the fluctuations are large because in the zone feeding the stream the concentration gradient is large.

Another reason for the higher temporal variation in the Hydrus-results is memory. In ANIMO, the relation between the discharge and the Cd-concentration depends only on the depth of the concentration front relative to the depth of the water table. However,

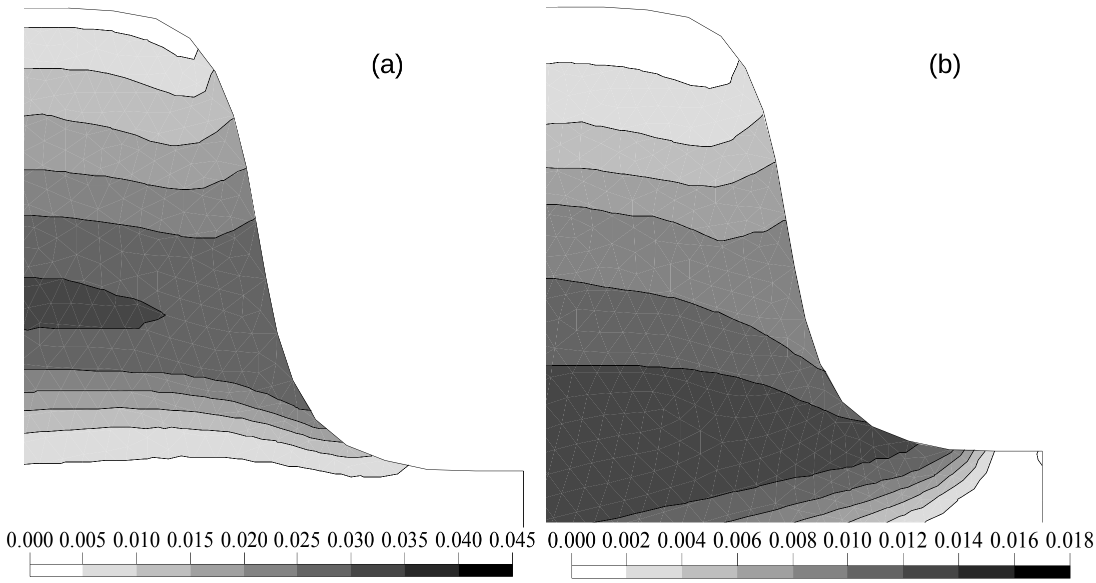

Fig. 4 Distribution of the Cd-concentration (µg cm^{-3}) close to the stream for the two time periods in Fig. 2: (a) winter in the years 5–6, and (b) winter in the years 27–28 (discharge occurs only through the stream bottom; area: 1.1 × 1.1 m).

for Hydrus-2D the flow history can influence the concentration of the discharge. A final effect is that as a result of transversal dispersion the front becomes somewhat less steep in the area of the stream, where the velocity of the water is higher. It is unclear how much these last processes exactly influence the discharge of Cd to the stream.

Outflow to two drainage levels

The differences between the results of Hydrus-2D and ANIMO turn out to be larger for outflow to two drainage levels than for one drainage level. In the scenario with transient flow conditions and conservative transport, the temporal variation differs considerably between ANIMO and Hydrus-2D. The total Cd-discharge to the stream is not much different. For the scenario with transient flow and adsorption, the basic pattern is similar to the case with one drainage level: the concentration rises faster in ANIMO than in Hydrus-2D. After 30 years, 8% more water and 36% more Cd is discharged through the drainage system in SWAP/ANIMO.

In Fig. 5 an example of the temporal variation in the concentration is presented. For ANIMO the concentration shows some abrupt jumps. These are caused by occasional drying up of the secondary drainage level with a depth of 0.5 m. When the groundwater level falls below 0.5 m, only discharge to the primary drainage level remains. The Cd-concentration of the pore water discharging to the primary drainage level is much lower than that discharging to the secondary drain level because the Cd-front is still shallow. The variation in the concentration is much smoother for Hydrus-2D, because two separate drains with a depth of 0.5 m are simulated in Hydrus-2D. These do not dry up simultaneously. Because of the convexity of the groundwater table the drain closest to the primary water course of 0.95 m depth dries up more often. The spatial pattern of the concentration in the cross-section reflects this asymmetry (Fig. 6).

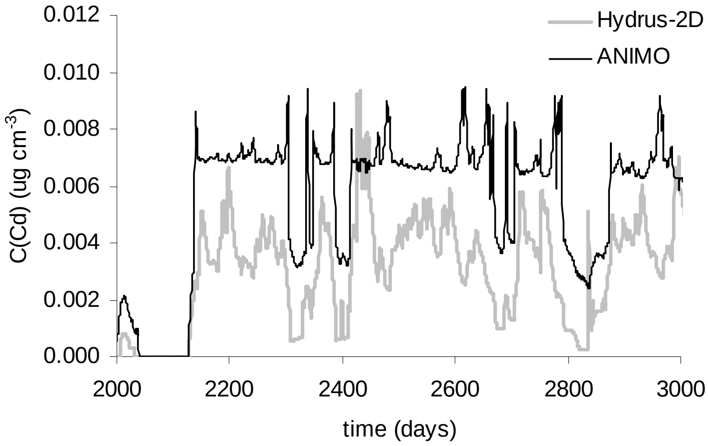

Fig. 5 Example of the Cd-concentration for a scenario with drainage to two levels.

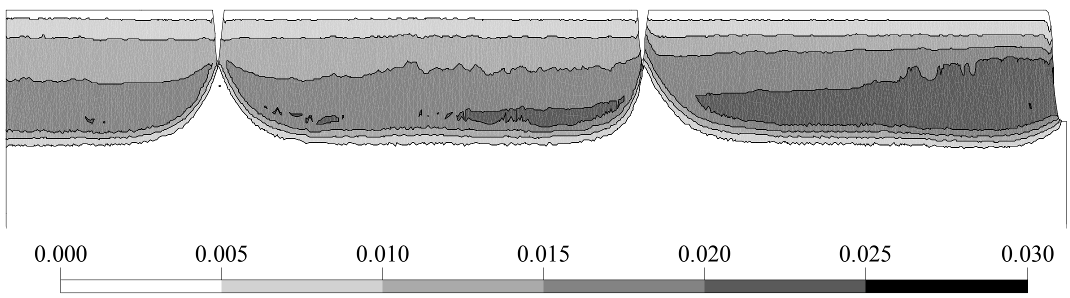

Fig. 6 Cd-concentration (μg cm^{-3}) in a cross-section after 3118 days simulated using Hydrus-2D (stretching factor vertical coordinate: 5, width cross-section: 45 m).

CONCLUSIONS

To test the capabilities of the quasi-2-D approach for simulating loading of surface water from groundwater, results of the quasi-2-D approach were compared to the results of a 2-D model for two scenarios: drainage to one and two levels at the field scale. For drainage to one level, the results of the quasi-2-D and 2-D approach are very similar for stationary flow conditions and conservative transport. For transient flow conditions with adsorption the results differ considerably. For drainage to two levels, the results differ considerably for conservative transport, especially on short-term temporal variation. When adsorption is included, the differences become even larger. Although it is difficult to link differences in results to differences in the models, it is clear that the quasi-2-D approach becomes less suitable for more complex flow conditions and adsorption.

REFERENCES

Groenendijk, P. & van den Eertwegh, G. A. P. H. (2004) Drainage-water travel times as a key factor for surface water contamination. In: *Unsaturated-Zone Modeling: Progress, Challenges and Applications* (ed. by R. A. Feddes, G. H. De Rooij & J. C. van Dam) (Papers for the Frontis Workshop, Wageningen, The Netherlands, October 2004), Published in Wageningen Ur Frontis Series, vol. 6, XXII. The Netherlands.

Hansen, S., Jensen, H. E., Nielsen, N. E. & Svendsen, H. (1990) *DAISY: Soil Plant Atmosphere System Model*. The Royal Veterinary and Agricultural University, no. A10. Denmark.

Kroes, J. G. & Roelsma, J. (1998) *ANIMO 3.5; User's Guide for the ANIMO version 3.5 Nutrient Leaching Model*. Wageningen, SC-DLO, Tech. Doc. 46. The Netherlands

Refsgaard, J. C. ,Thorsen, M., Jensen, J. B., Kleeschulte, S. & Hansen, S. (1999) Large scale modelling of groundwater contamination from nitrate leaching. *J. Hydrol.* **221**, 117–140.

Schoumans, O. F. & Silgram, M. (eds) (2003) *Review and Literature Evaluation of Quantification Tools for the Assessment of Nutrient Losses at Catchment Scale*. EUROHARP report 1-2003, NIVA report SNO 4739-2003, Oslo, Norway.

Schoumans, O. F., Roelsma, J., Oosterom, H. P., Groenendijk, P., Wolf, J., van Zeijts, H., van den Born, G. J., van Tol, S., Beusen, A. H. W., ten Berge, H. F. M., van de Meer, H. G. & van Evert, F. K. (2002) *Nutriëntenemissie vanuit landbouwgronden naar het grondwater en oppervlaktewater bij varianten van verliesnormen*. Modelberekeningen met STONE 2.0. Clusterrapport 4: Deel 1, Alterra, Wageningen, The Netherlands.

Šimůnek, J., Šejna, M. & van Genuchten, M. Th. (1999) *The HYDRUS-2D Software Package for Simulating the Two-Dimensional Movement of Water, Heat, and Multiple Solutes in Variably-Saturated Media*. Version 2.0. US Salinity Laboratory, Agricultural Research Service, US Department of Agriculture, Riverside, California, USA.

van Dam, J. C., Huygen, J., Wesseling, J. G., Feddes, R. A., Kabat, P., van Walsum, P. E. V., Groenendijk, P. & van Diepen, C. A. (1997) Theory of SWAP, simulation of water flow, solute transport and plant growth in the Soil-Water–Atmosphere–Plant environment. Report 71, Department of Water Resources, WAU. Technical document 45, DLO Winand Staring Centre, Wageningen, The Netherlands.