Functional Sensitivity Analysis of Four Methods to Generate Soil Hydraulic Functions

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ABSTRACT

Rapid advances in model building have led to the understanding that applicability of future simulations depends, to a great extent, on the availability of accurate soil hydraulic functions obtained with efficient methods rather than on new models. In this study, four different methods were used to generate hydraulic functions: Method A, direct on-site measurement; Method B, use of measured hydraulic functions averaged on a regional scale; Method C, use of measured hydraulic functions averaged on a national scale; and Method D, use of van Genuchten parameters correlated with soil texture and organic-matter content. Accuracy of these methods was tested by comparing the simulated water storage with the measured water storage of the upper 0.5 m of three soil profiles over a period of 7 yr. Differences in performance of the four methods were not significant. Agreement between measured and simulated water storage was best, however, when directly measured hydraulic functions (Method A) were used. Next best agreement was obtained when continuous (Method D) and two types of class pedotransfer functions (Methods B and C) were used, which relate textures and soil horizons to physical characteristics. Costs involved in obtaining directly measured soil hydraulic functions are prohibitively high, compared with costs for the other methods. With regard to both accuracy and costs, the development of a data base of measured soil hydraulic functions and use of this information to derive continuous and class pedotransfer functions assures, in many cases, optimal spending of limited available resources.

SIMULATION MODELS have become indispensible research tools for describing movement of water and solutes into and through the unsaturated zone. Models, ranging from very simple to highly complex, are being used increasingly to evaluate effects of management practices on crop yield and groundwater quality (Dumanski and Onofrei, 1989; Addiscott and Wagenet, 1985; Penning de Vries and van Laar, 1982). This use of models for research and management purposes has led to the understanding that different problems ask for different approaches. Sometimes an in-depth approach is needed to study a problem in detail and sometimes a simple approach is appropriate when addressing a general question (Bouma, 1989).

The availability of input data is pertinent to the use of models. As our ability to simulate more complex systems increases, the accuracy of future simulations may well depend on the availability of accurate input data. Lack of accurate soil hydraulic functions, in particular, is often considered to be a major obstacle for making progress (van Genuchten et al., 1989). Formulated in a positive way, using available data is acceptable as long as we are aware of the uncertainty of our predictions. Use of "perfect" data, if it exists at all, is often not necessary because many problems do not ask for exact solutions. At the same time, use of "perfect" data obtained by direct measurement of soil hydraulic functions is often prohibitive because of the cost and time involved. For every problem, the challenge is to identify a modeling approach that provides a quantitative estimate of system behavior from a relatively simple and cheap data set while providing an indication of the uncertainty of predictions.

In this study, a functional sensitivity analysis was conducted in which the effects on simulation of soil water storage were evaluated for four different methods to generate soil hydraulic functions. Methods to generate soil hydraulic functions included Method A, relatively expensive direct on-site measurement; Method B, use of measured hydraulic functions averaged by soil horizon on a regional scale; Method C, use of measured hydraulic functions averaged by soil horizon on a national scale; and Method D, use of van Genuchten parameters correlated with soil texture and organic-matter content. Simulated water storage in the upper 0.5 m of three soil profiles was compared with measured water storage for a period of 7 yr. The SWATRE model being used has been validated for this watershed in a previous study (Wösten et al., 1985), as well as for other studies (Feddes et al., 1988).

MATERIALS AND METHODS

Site Characteristics

The Hupselse Beek watershed is situated in the eastern part of the Netherlands and has been an experimental study area of the National Dutch Water Service for 20 yr. The area covers 650 ha, and its altitude varies between 22 and 33 m above mean sea level. Land use is predominantly agricultural: 80% pasture, 12% arable land, and 8% forest. The area is underlain by Miocene clay sediments starting between 0.2 and 10.0 m below the present soil surface. The area was affected by glaciers that deposited boulder clay (glacial till) in an early Pleistocene period. Later, aeolian sands were deposited over the entire area, forming a surface relief that is quite different from the relief of the underlying boulder-clay surface. Wösten et al. (1985) presented a detailed soil map of the area.

In this study, water storage was simulated for three sites in two dominant mapping units in the area. Figure 1 shows the soil profiles for the three sites. The soil horizons A, B, and C indicate sandy horizons; D1 is boulder clay and D2 is Miocene clay. According to Soil Survey Staff (1975), Sites 1 and 3 are classified as sandy, siliceous, mesic Typic Haplaquods and Site 2 as a sandy, siliceous, mesic Plaggept. The boulder clay at Site 3 is variable in composition, with sand veins adjacent to heavy clay. At the same time, the starting depth of the boulder clay varies strongly over short distances (Bouma et al., 1989). As a result, profiles at different sites in this mapping unit may differ from the profile at Site 3. Groundwater levels for Site 1 range from 0.4 m below the soil surface in winter to 1.4 m in summer. Ranges are from 2.2 m in winter to 2.9 m in summer for Site 2, and from 0.6 m in winter to 1.3 m in summer for Site 3.

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Generating Soil Hydraulic Functions

Soil water-retention and hydraulic-conductivity curves were generated for each soil horizon using the four different methods.

A. Direct Measurement. Hydraulic conductivities of the different soil horizons were measured using a combination of the following four methods: (i) the column method (Bouma, 1982) for the vertical saturated hydraulic conductivity (K_s), (ii) the crust test (latest version of the method reported by Bouma et al., 1983) for unsaturated conductivities when the pressure head, h, was between 0 and -5 kPa, (iii) the sorptivity method (Dirksen, 1979) for conductivities in the case of sand when $h < -5$ kPa, and (iv) the hot-air method (Arya et al., 1975) for conductivities in the case of loam and clay when $h < -5$ kPa. Soil water retention was obtained by slow evaporation of wet undisturbed samples in the laboratory, as reported by Bouma et al. (1983). In these samples, pressure heads were periodically measured with transducer-tensiometers while, at the same time, subsamples were taken to determine water contents, θ. This procedure yielded points relating h and θ. Water contents corresponding with $h < -80$ kPa were obtained by conventional air-pressure methods (Klute, 1986). A set of 13 measured soil water-retention and hydraulic-conductivity curves were used for Method A to provide model input for all horizons of the three soils, as illustrated in Fig. 1.

B. Use of Measured Soil Hydraulic Functions Averaged by Soil Horizon on a Regional Scale. In the study by Wösten et al. (1985), the hydraulic functions of all soil horizons distinguished in the Hupselse Beek watershed were measured in sixfold by using the described measurement techniques. Sampling locations were chosen at random within the various delineated areas of the soil map. Replicate measurements for each horizon were used to calculate the average hydraulic functions for every horizon. After comparison of the hydraulic functions of the different horizons, only those horizons were distinguished whose soil hydraulic functions differed significantly. Their number was lower than the number of horizons that was distinguished by pedological classification, because pedological differences do not necessarily correspond with differences in hydraulic functions.

Hydraulic functions averaged on a regional scale were used in Method B to obtain soil hydraulic data for the soil profiles at the three sites. A set of four different soil water-retention and hydraulic-conductivity curves was distinguished: A1, Aan, B2 + C11 + C12 + C11g, and D1 + D2.

C. Use of Measured Soil Hydraulic Functions Averaged by Soil Horizon on a National Scale. The described techniques have been used to measure hydraulic functions for a large number of soil horizons in the Netherlands. For application on a national scale, soils were classified according to soil texture (as used by the Netherlands Soil Survey Institute) and type of horizon, either topsoil (A horizon) or subsoil (B and C horizons). This classification resulted in 20 different soil groups comprising a total of 197 individual curves. Tabulated forms of the averaged curves for the 20 soil groups were presented by Wösten et al. (1987). As a set, the curves form a unique data base covering the broad spectrum of soils in the Netherlands. This set is increasingly being used to simulate regional soil water regimes. In Method C, the averaged curves for three soil groups from the national set were used in this study to provide hydraulic functions for the A1 + Aan, B2 + C11 + C12 + C11g, and D1 + D2 horizons.

D. Use of Soil Properties to Predict Soil Hydraulic Functions. Analytical expressions of van Genuchten (1980) for the water-retention and hydraulic-conductivity curves were fitted simultaneously to the set of measured hydraulic functions for a wide range of soils in the Netherlands (Wösten et al., 1987). Wösten and van Genuchten (1988) used regression analysis to relate estimated model parameters to more easily measured soil properties such as bulk density and percentages of silt, clay, and organic matter. The resulting functions predict the hydraulic parameters for all horizons shown in Fig. 1 from their corresponding texture values.

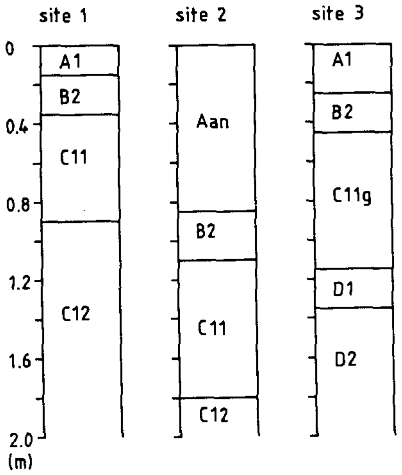

Fig. 1. Soil profiles at the three sites.

Methods B, C, and D qualify as pedotransfer functions, which relate different land and soil characteristics with one another and to land qualities. Methods B and C can be described in terms of class pedotransfer functions, relating soil horizons to associated hydraulic functions. Method D can be described in terms of a continuous pedotransfer function, relating, e.g., soil texture, bulk density, and percentage organic matter to associated hydraulic functions (Bouma and van Lanen, 1987; Bouma, 1989).

Statistical Data Analysis

Two statistical properties were calculated to evaluate the differences between measured and calculated water storage. The mean residual error (ME) was defined as

$$\mathrm{ME} = (1/n) \sum_{i=1}^{n} (x_i - y_i) \qquad [1]$$

and the mean squared residual error (MSE) was defined as

$$\mathrm{MSE} = (1/n) \sum_{i=1}^{n} (x_i - y_i)^2 \qquad [2]$$

where n = number of data points of measured and calculated water storage, x = measured water storage, and y = calculated water storage.

Calculated water storages are regressed vs. x and are presented in a graph that includes the 1:1 line.

Mean residual error is a measure for the bias in the simulation results. Values close to zero indicate that measured and calculated water storages do not differ systematically from each other or, equivalently, that there is no consistent bias. Values that differ greatly from zero indicate the presence of systematic deviation or bias.

Mean squared residual error is a measure for the scatter of the data points around the 1:1 line. Low MSE values indicate little scatter, and high MSE values indicate large scatter. Low MSE values also imply low ME values.

The variance of the differences between measured and calculated water storages (VAR) was estimated as

$$\mathrm{VAR} = \frac{n(\mathrm{MSE} - \mathrm{ME}^2)}{n - 1} \qquad [3]$$

With the assumption of normal distribution and independence of differences between measured and calculated water storages, the half width of the 95% confidence interval for ME was calculated as

$$t\left(\frac{\mathrm{VAR}}{n}\right)^{1/2} \qquad [4]$$

where t = the value of the Student's t distribution for $\alpha = 0.05$ and $n - 1$ degrees of freedom. This half width of the confidence interval is used to examine, for each of the four methods, whether differences between measured and calculated water storages are statistically significant.

An analysis of variance (ANOVA) revealed if there were statistically significant differences between the four methods with respect to their approximation of the measured water storages. With the assumption of independence of both ME and MSE values, ANOVA was carried out on the twelve ME and twelve MSE values calculated (four methods, with the three sites as repetitions).

Expenses of the Different Methods

The four methods used to generate soil hydraulic functions differed considerably in terms of costs. In Method A, hydraulic functions were measured for each of the 13 horizons, which constitute the soil profiles at three sites in the watershed. These sites represented a pedon area of 10 m^2 each. Measurement of the hydraulic functions took an estimated labor cost of 3 d per horizon, or a total of 39 d of operational activities. Hydraulic functions averaged on a regional scale (Method B) were obtained from replicate measurements of identical horizons at different locations within the delineated areas. As a consequence, initial investment to obtain average functions was, in principle, the same as the cost of the total number of measurements made in the area. The nine horizons distinguished in the Hupselse Beek watershed were measured in sixfold to obtain average functions (Wösten et al., 1985). This required a total of $9 \times 6 \times 3 = 162$ d. Once these average curves were obtained, on-site visits to establish the type of soil horizons were satisfactory to generate hydraulic functions for the entire watershed area of 650 ha. This required little operational activity, perhaps 1 d.

Hydraulic functions averaged on a national scale (Method C) were derived from a data base comprising a total of 197 individual curves. The initial investment to obtain these average curves was therefore $197 \times 3 = 591$ d. The functions averaged on a national scale provide information for the entire Netherlands, an area of about 3 000 000 ha. Analogous to conditions on a regional scale, operational activities are restricted to on-site visits to establish the type of soil horizons. This takes an estimated 5 d of operational activities. The continuous pedotransfer functions used in Method D were derived from the same data base as used for Method C. Therefore, initial investment and area covered were the same as with Method C. In this case, however, operational activities were not restricted to on-site horizon identification, but also included measurement of soil texture of the identified horizons. This took an estimated 10 d of operational activities for 13 horizons.

Thus, direct measurement (Method A) implies a very high investment per unit area, compared with Methods B, C, and D. After making a major initial investment for the determination of a standard set of measurements, Methods B, C, and D can be executed with little effort. Besides the fact that Method A is prohibitively expensive, when average project budgets are considered, the measurements are site-specific and cannot be extrapolated. The next project will again require identical measurements. Since Method A is not a practical possibility, research has to focus on whether investments required to execute Methods B, C, and D are justified. This would be the case if water storages are equally well described by calculating them using data obtained with Methods B, C, and D, compared with data obtained with Method A.

Simulation of Soil Water Storage

Soil water flow was simulated with the model SWATRE (Soil Water Actual Transpiration Extended; Feddes et al., 1978; Belmans et al., 1983), which is a one-dimensional, finite-difference model that describes transient, unsaturated water flow in a heterogeneous soil–root system that may or may not be under groundwater influence. In this study, soil physical input data for every horizon of the three sites were obtained with four different methods. Calculations were made for a grass crop by using a sink term to simulate water uptake by plant roots. Rooting depth was 0.2 m for Site 1 and 0.25 m for Sites 2 and 3.

The meteorological station of the Hupselse Beek watershed provided daily precipitation and daily potential evapotranspiration values for the period March 1976 to December 1982. Potential evapotranspiration values were calculated according to Thom and Oliver (1977). Groundwater levels for Site 1, which is located at the meteorological station, were measured daily. Groundwater levels for Sites 2 and 3 were measured every week. After correlation of the weekly levels for Sites 2 and 3 to the daily levels of Site 1, daily groundwater levels for Sites 2 and 3 were estimated. These daily groundwater levels for the period March 1976 to December 1982 served as the lower boundary condition for the SWATRE simulations.

The SWATRE model was used to make daily calculations for an uninterrupted 7-yr period from March 1976 to December 1982. To a depth of 0.5 m, the soil profiles were schematized into five compartments with a thickness of 0.10 m each and, deeper than 0.5 m, into eight compartments with a thickness of 0.20 m each. By accumulating water contents of the top five compartments, cumulative water storages of the first 0.5 m of the soil profiles were calculated.

In a previous study for Site 1, van Vuuren (1984) demonstrated that hysteresis affected the results. Use of an "assumed" adsorption water-retention curve for simulation of wetting after the exceptionally dry conditions of 1976 gave results that agreed better with measured water contents when compared with results obtained with the use of a measured desorption curve. However, measured adsorption curves were not available. Therefore, data points for this very dry period, which has a probability of occurrence of only 2%, were omitted from the data analysis in this study.

Measurements of Water Content with the Neutron Probe

As part of ongoing research in the Hupselse Beek watershed, water contents at different locations have been measured since 1976 with a neutron probe. Calibration curves were established for the different soil horizons in the watershed to provide an accurate conversion of neutron counts into water contents.

Distances between locations where neutron-probe measurements were made and locations where soil samples were taken for measurement of hydraulic functions were about 10 m for each site in order not to disturb the neutron-probe readings. At the three sites considered in this study, neutron-probe measurements were made once every 2 wk to a depth of 2 m below the soil surface. In the topsoil, measurements were made at 0.25-, 0.35-, and 0.45-m depth. Water contents were such that the radius of the sphere of influence for neutrons was about 0.25 m (Gardner, 1986). Therefore, water contents at these depths could be used to calculate the water storage of the first 0.5 m of each of the three soil profiles. The large quantity of measured values of soil water storage over the period 1976 to 1982 form an exceptional data base for validation of values of soil water storage as simulated with the four different methods discussed above.

RESULTS AND DISCUSSION

Measured and calculated water storages show a pattern that agrees with what might be expected from the prevailing weather conditions over the years 1976 to 1982. The dry year 1976 and, to a lesser extent, also 1982 showed, as expected, a strong decrease in water storage in the summer period while, in the wet years 1977 and 1979, changes in water storage over the seasons were less pronounced. The general trend of water storages calculated with the four methods over the years agrees well with measured values for all sites. For reasons of brevity, Fig. 2 shows only results obtained with Method A, for the characteristic period March 1976 to March 1978, of measured and simulated water storages in the upper 0.5 m of Site 1. Drying of the upper 0.5 m of the soil profile in 1976 was well predicted by simulation. There was also good agreement between measured and calculated values over the period March 1977 to March 1978. However, wetting of this top layer in the winter 1976–1977 was systematically overestimated with simulation. The main reason for this discrepancy is that the desorption water-retention curve was used in the simulation model, while use of an adsorption curve would have been more realistic for wetting under these dry conditions (see discussion above).

Table 1 summarizes the results of the statistical analysis of the differences between measured and calculated water storages for the four methods and the three sites. For each site and for each method, values are presented for the number of data points, the ME, the half width of the 95% confidence interval of the ME, and the MSE. Figure 3 shows the results for Site 1 of the regression of calculated water storage vs. measured values for the four methods. The 1:1 line, as well as the regression line, are included. The figure provides a good visual reflection of results of the statistical analysis in terms of bias and scatter of data points. Comparable expressions were obtained for the other two sites.

The slopes of the regression lines varied from 0.61 for Method D at Site 2 to 1.40 for Method C at Site 3. Variation in r^2 (r is the correlation coefficient) was from 0.46 for Method D at Site 2 to 0.85 for Method B at Site 3.

For Sites 1 and 2, ME values for Methods A and D are relatively close to zero, compared with the values for Methods B and C. For Site 3, there is not such a trend. When ME values differ from zero, this indicates that measured and calculated water storages deviate in most cases. The ME values, together with the calculated half widths of the 95% confidence interval, indicate that these deviations are statistically significant for all methods and all sites except for Methods A and D for Site 2. Only in these two cases is the hypothesis that measured and calculated values are the same (i.e., ME = 0) not rejected. The positive ME values for Site 1 indicate that simulated water storages are systematically lower than measured values. This result is supported by Fig. 3, where the majority of

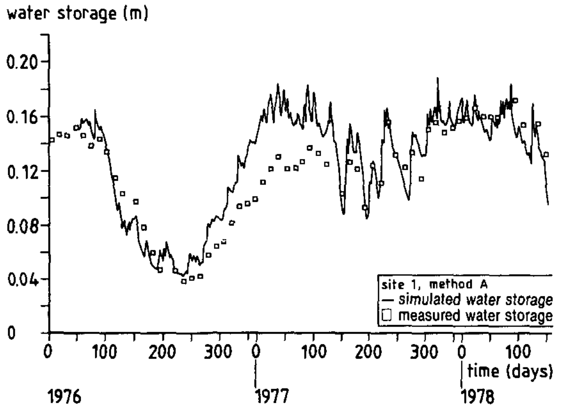

Fig. 2. Yearly trend in measured and calculated water storages of the upper 0.5 m at Site 1 when using Method A (direct measurement).

Table 1. Results of the statistical analysis, for each of the four methods, of the differences between measured and simulated water storages.

Method	n	Mean residual error (ME)	Half width of the 95% confidence interval of ME	Mean squared residual error (MSE)
		cm	cm	cm^2
Site 1				
A	132	1.329	0.317	5.118
B	132	2.433	0.319	9.315
C	132	2.615	0.347	10.857
D	132	2.010	0.295	6.953
Site 2				
A	154	0.1556	0.317	3.954
B	154	−1.8966	0.353	8.494
C	154	1.6840	0.341	7.391
D	154	−0.2437	0.332	4.383
Site 3				
A	155	−1.223	0.312	3.475
B	155	−1.242	0.211	3.304
C	155	−1.044	0.250	3.533
D	155	−1.497	0.181	3.534

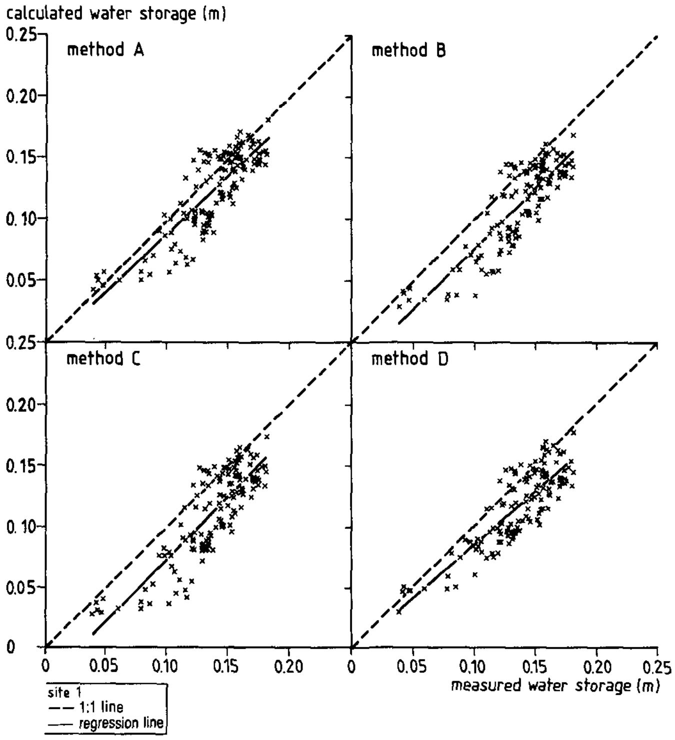

Fig. 3. Comparison between measured and calculated water storages at Site 1 for a 7-yr period, using the four methods.

data points are found below the 1:1 line. The negative ME values for Site 3 indicate an opposite effect; in this case, simulated water storages are systematically higher than measured values. In many simulation-model studies, such systematic deviations are corrected in the model-calibration phase, thereby eliminating their negative effect on model output. In this study, we have chosen to present the real output data because emphasis is on an accurate simulation as well as on comparison of the four methods.

Low MSE values indicate little systematic deviation between measured and calculated values, as well as absence of a systematic trend in the scatter of data points around the 1:1 line. While systematic deviations, as also expressed by high ME values, can be corrected by model calibration, trends in the scatter of data points are not corrected and are undesirable. Therefore, low MSE values are desirable. Comparison of the MSE values in Table 1 shows that, for Sites 1 and 2, Method A had the least dispersion around the 1:1 line. Next, Method D performed best, while Methods B and C showed the most dispersion. For Site 3, MSE values for the methods are about the same.

The ANOVA for both ME and MSE shows that differences between methods were not statistically significant. Since agreement between measured and calculated water storage is not highly influenced by the choice of the method used to generate soil hydraulic functions, this choice can be based on other considerations such as cost or ease of use.

SUMMARY AND CONCLUSIONS

Four methods were used to generate soil hydraulic functions for use in a soil-water simulation model. Calculated water-storage values for the upper 0.5 m of three sandy soils were compared, for a period of 7 yr, with water-storage values measured with a neutron probe. Comparison of the different methods showed that, in most cases, calculated values deviate systematically from measured values. However, when a well-tested simulation model is used, this systematic deviation can be corrected in the model-calibration phase. Evaluating the four methods in terms of ME and MSE indicates that direct measurement of hydraulic functions (Method A) gave the best results, followed by continuous pedotransfer functions (Method D) and averaged regional and national functions (Methods B and C). Analysis of variance shows that differences between methods with respect to their approximation of measured water storages were not significant. Compared with Methods B, C, and D, the costs of using Method A are very high, making it an unrealistic alternative. Methods B, C, and D require a substantial initial investment for the determination of a standard set of measured hydraulic functions. Once such a set is established, however, its use is attractive in terms of accuracy and cost.

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