Soil Water Balance: Field Observation and Simulation

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Abstract

A water balance evaluation was performed to study the hazardous potential for the groundwater of a disposal site for remains of a paper mill. The study is relying on a field measuring site and on a computer simulation. Owing to computer simulations only one field measuring site was necessary for the given task. The observed changes of water content in the soil profile provide input data for the computer model and are used for its calibration. The calibrated simulation model serves as a means for the interpretation of different scenarios, such as variation of soil profile, hydraulic conductivity and plant factors.

1 Introduction

A measuring site was established in 1994 to collect parameters for the soil water balance in a manmade soil profile. A data acquisition system [1] with a solar panel as energy source was used for data collection at the measuring site. Sensor readings, like water content, temperature and gypsum block values were recorded every hour on a data logger. The main goal was to study the water balance with respect to the effluent amount of water to estimate the risk to contaminate the groundwater [2]. The soil profile consists of two layers. The depth of the top clay layer varies from 0.4 to 1.0 meter. The second layer (approximately 3 m) contains a high percentage of coarse grained organic material (remains from a paper mill). Underlying is a fractured conglomerate

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with a mild slope facing east to west. The surface is very rough and covered with grass and weeds, the inclination is horizontal. To gain information about the quality of the effluent, a chemical analysis was performed. Soil water samples were taken at the measuring site with suction cups and a sample of the lower layer was taken into the laboratory, soaked in water and the effluent was analysed. The evaluated chemical parameter showed the high organic content and proved the need for a soil water balance.

To calculate the flow rates, for more flexibility, to look at space varying conditions and to be able to forecast possible measures to reduce the outflow rate the use of a numerical model was proposed. The in situ measurements provided data for the calibration of the computer model and the initial conditions for the water balance simulation.

2 Data collection

At four locations trenches were dug through the top layer and one trench was made to the full depth of the deposited material. In the top layer block type and temperature sensors were placed around the data acquisition system. Block type sensors gave an indication of the wetting and drying cycles. At least two sensors were placed at each spot, one near the surface and the other near the boundary to the lower layer. The recorded soil water tension allowed the estimation of water movement or the passing of the wetting front. Temperature readings were necessary in connection with block type sensors for temperature compensation. Block type sensors were used where a tight contact with the surrounding soil was ensured. The second layer contains a highly coarse matter, hence other sensors had to be installed. The second restriction was the organic content of this layer. Both restrictions led to the choice of dielectric water content sensors. By performing a laboratory calibration of the dielectric sensors a soil specific relation for soil water content and dielectric constant was achieved [3]. The sensors were placed into the undisturbed soil from the dead end of the trench, in a depth of 0.10 m, 0.35 m, 1.15 m, 1.75 m and 2.90 m (Fig. 1). Additionally one block type sensor was placed next to a dielectric probe. Water content, temperature and Watermark (block type sensors) readings were collected for a period of one year. Precipitation and evaporation values were taken from an official hydrologic measuring site nearby. The soil physical situation, top layer with low hydraulic conductivity and restricted outflow due to the underlying conglomerate, caused a more or less constant water content in the lower layer. The observed water content distribution (Fig. 2) showed a significant change for the summer period and for the sensors in the top layer only. The deepest sensor reached a value close to the saturation value measured in the laboratory.

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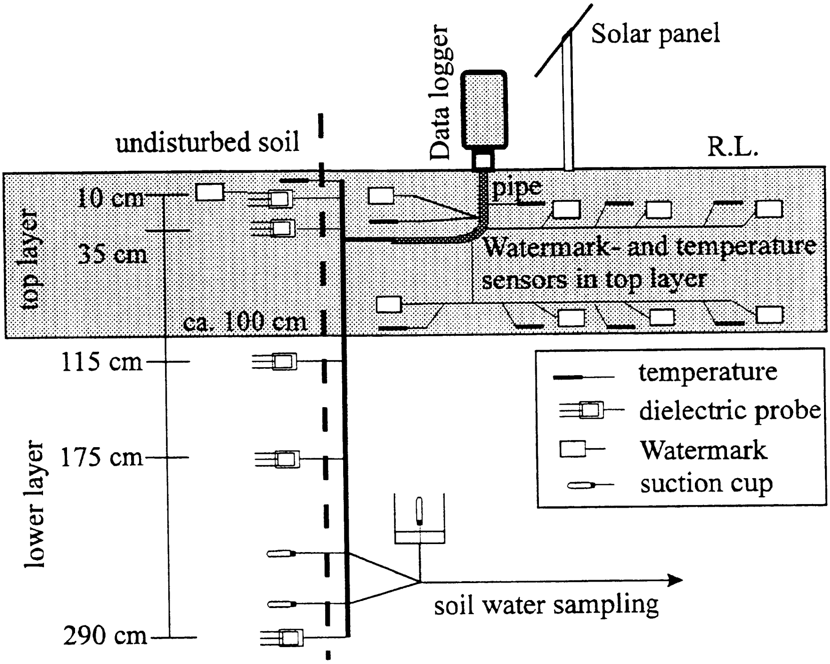

Figure 1: Vertical cross-section of field measuring site

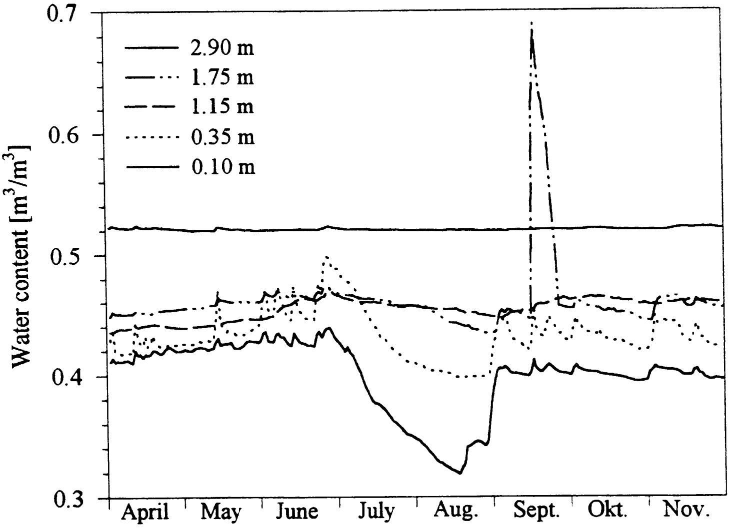

Figure 2: Water content in situ, April to November 1995

Besides the field data soil samples were taken and analysed to determine the hydraulic conductivity, the soil heterogeneity and to calibrate the dielectric water content sensors. A calibration was needed because the dielectric sensors are adjusted to sand, silt and clay and do not account for a high organic content.

3 Simulation model

The numerical model LEACHM (Leaching Estimation And Chemistry Model) developed by Wagenet and Hutson [4] was used for the simulation. It comprises of four different independent models to describe nitrogen transport and transformation, pesticide displacement and degradation, transient movement of inorganic ions and the water regime. Estimates of plant growth, water and solute uptake by plant roots are included in all four models, together with flexible input features for precipitation and evaporation of water. For the given task the water regime model was applied to a layered soil. The program is written in FORTRAN 77 and is based on the numerical solution of the Richard's equation as a means to predict water content, fluxes and potentials. The accessibility to the source code makes adaptations possible. Input requirements for the model are the soil hydrological characteristics (hydraulic conductivity and water retention curve), boundary conditions, source and sink terms (precipitation, irrigation, evaporation and transpiration). The soil water retention curve is approximated with the relation proposed by Campbell. Originally this relation is derived by means of a choice out of four calculation algorithm, related to the particle size distribution. To be able to include a known soil water retention curve the new option - read from input data file - was introduced into the source code [5]. To include the plant cover, the options are: none, constant cover and plant growth simulation. For plant parameters wheat is set as default. For other plants the root depth and the plant cover ratio have to be empirically adjusted.

A simulation run starts at time 0^{00} of the first day. For each consecutive day the root growth and density is calculated and the potential evapotranspiration evaluated, for each time step within a day the appropriate length, the actual evapotranspiration, the root water uptake and the soil water tension are determined. The actual transpiration of the existing plant cover is the minimum out of potential evaporation and water transport to the root zone. In a next step the transport of water is simulated and transferred into changes of water content and soil suction. Outputs are prepared at selected time steps.

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4 Simulation results

The computer simulation serves to calculate outflow rates for varying depths or permeabilities of top-layer and for estimating the influence of vegetation [6]. The model was stepwise calibrated with the collected data. First representative values for the hydraulic conductivity and the soil water retention curve were found utilising one layer models. The laboratory soil water retention curve was improved by taking into account the measured soil water tension (Watermark values) in relation to water content readings. Then a two layer model was set up and boundary conditions were identified. The measurements gave evidence for designating the lower boundary like a lysimeter-type condition, because the fractured conglomerate does not provide a free outflow. Up to this time the plant factors were kept constant. Adjustments related to the growing cycle finalized the calibration work. Then the model was verified with the measured data in a simulation run from April to November. The initial conditions were set according to the measured values in April. Taking into account that a simple two layer model with constant hydraulic conductivity for each layer is used and that the recorded precipitation is an approximation of the actual one right at the measuring site, the simulation results (Fig 3) are found to be satisfactory. Water content calculations are presented in accordance with the placement depth of the sensors. The drying period during summer is well represented and the other simulated curves show constant values similar to the measurements.

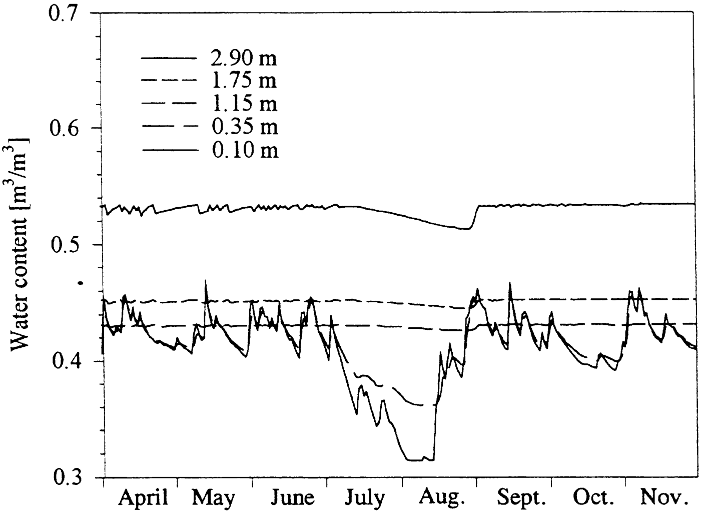


Figure 3. Simulated water content in situ, April to November 1995

From the simulated soil water distribution a water balance calculation is made. The given precipitation is cumulated and compared with the outflow at the lower boundary (Fig. 4). Approximately two thirds of the precipitation is passing through the soil profile. Starting with April, a small time shift between precipitation and outflow is visible. With the beginning of the growing season the two lines diverge due to water uptake by plants. The further increase of plant water requirement in July and August in combination with very little precipitation resulted in no outflow at all for the summer period. The only remarkable retention occurs at the end of August and September, when the outflow differs from the precipitation considerably. After a short dry period in October the outflow reaches again a similar pattern as the input.

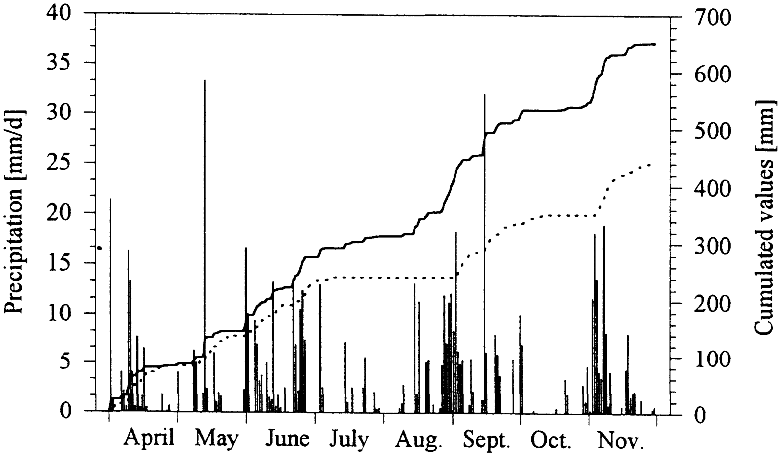


Figure 4. Outflow at bottom and precipitation

To get more detailed information about the water balance, an output file is provided comprising all considered flow terms. This is especially of importance for the distinction between different mass balance terms and to compare different soil profiles, plant covers or hydraulic conductivities and to justify the effects of measures which could be taken, such as an increase of the surface runoff, to reduce the outflow. As an illustration the water balance for the existing soil profile is compared with calculations for a different top layer depth. The considered mass balance terms are cumulated and at a selected time step, e.g. at the end of a simulation run, stored in an output file (table 1).

Depth of top layer	1.0 m	0.5 m
	cumulated outflow · 10^{-3} [m3/m2]	
Cum. Infiltration	652.6	
Cum. Runoff	0.2	
Cum. Leachate	**441.9**	**420.4**
Cum. Evaporation	75.2	83.8
Cum. Transpiration	136.3	146.1
Profile Water Change	3.3	0.8
Check	-4.1	1.4

Table 1: Final mass balance at the end of a simulation run

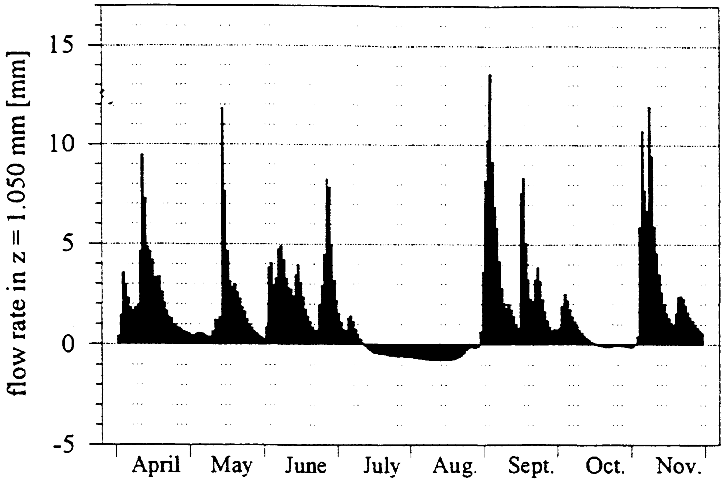
In profile water change the initial water content is compared with the present one. The cumulated runoff is a result of the rate of precipitation exceeding the infiltration. As an indication about the quality of the calculations and as a hint for possible errors in the input file, a mass balance term named as check is included in the output file. The error in the presented example is less than one percent.

To explain the reduction of the cumulated leachate for a thinner top layer the flow rate is calculated just below the boundary ($z = 1050$ mm and $z = 550$ mm) between the top and the bottom layer (Fig. 5).

During the summer period in both cases water is moving upwards out of the lower layer. The amount of water depends on the thickness of the top layer, a thinner layer provides more water supply upwards during summer leading to a higher transpiration and evaporation and the deep drainage has higher maximums and shows less water retention. A similar result is obtained by comparing calculations for different hydraulic conductivities.

The simulation showed, that the soil profile has very little water retention capacity. The evapotranspiration was found to be less than expected, especially for deeper or less permeable top layers. The precipitation did not exceed the infiltration capacity and hence did not cause a significant surface runoff. Besides the given variations of soil layer depth and conductivities the plant cover is the only variable but a significant reduction of the outflow can only be achieved during summer.

a) top layer 1.0 m



b) top layer 0.5 m

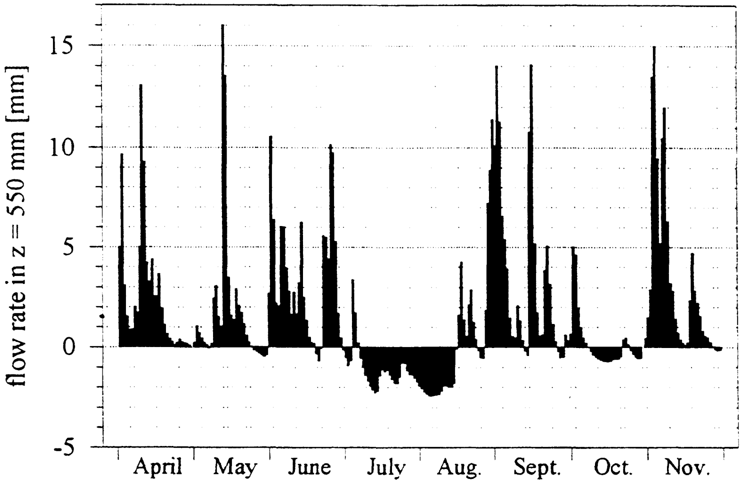


Figure 5. Flow rate between layers; a) top layer depth 1,0 m and b) top layer depth 0,5 m

5 Conclusion

The field measurements gave a reliable record of the changes of the soil water content and made an estimation of the water retention capacity possible. However, they did not provide information about the involved mass balance terms. In combination with the laboratory analysis the field data proved

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invaluable for the simulation. The simulation extended the value of the measurements not only by calculating the soil water balance but also by evaluating different scenarios. To get the same amount and quality of information by measurements only, more field work would be necessary, obviously resulting in an increase of costs.

As a final conclusion the combination of measurements and simulation enabled to optimize the process of gaining satisfactory results at reasonable costs.

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