A GIS integrated distributed approach for non-point source pollution modelling

FAYCAL BOURAOUI, GEORGES VACHAUD, RANDEL HAVERKAMP & TAO CHEN
Laboratoire d'Etude des Transferts en Hydrologie et Environnement, CNRS UMR 5564 INPG UJF, BP 53, F-38041 Grenoble cedex, France

THEO A. DILLAHA
Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061-0303, USA

Abstract Agricultural nonpoint source pollution is a very significant source of surface and groundwater quality problems. Distributed modelling is probably the most appropriate approach to quantify nonpoint source pollutant load and to determine the critical areas within a basin which are responsible for a disproportionate amount of contamination. The objective of the paper is to describe a distributed model developed recently for the simulation of surface and subsurface water movement which is the first step in modelling nonpoint source pollutant transport in the vadose and saturated zones. The model was successfully tested on an agricultural basin and was very responsive to management practices and climatic changes.

INTRODUCTION

The study of nonpoint source (NPS) pollution and its impacts on surface and groundwater quality has emerged as an environmental priority. Modelling is the most cost effective means for determining the impact of management alternatives on NPS loading. An integrated approach is necessary for a better understanding of the dynamic interactions between the different processes involved in nonpoint source pollution. Two fundamental aspects have to be addressed in the study of the transport processes through the soil to the ground water: modelling of the whole drainage basin as an entire system; characterization of the influence of spatial and temporal variability of the soil characteristics and management practices on the quality and the quantity of the groundwater recharge. The present paper describes a comprehensive distributed model for simulating water transport through the unsaturated and saturated zones.

MODEL DESCRIPTION

The following modelling approach is based on the concept of ANSWERS (Areal Non-point Source Watershed Environment Response Simulation; Bouraoui & Dillaha, 1996), a continuous, distributed parameters, nonpoint source pollution surface model for simulating infiltration, runoff and sediment transport. The basin is discretized into a matrix of square elements where topographic, soil hydrodynamics and crop characteristics are uniform. The model allows a vertical discretization to account for water movement
through the soil profile from the surface to the aquifer. The model is based on a daily water balance where the following flow phenomena are considered: infiltration, surface flow, drainage, evapotranspiration and groundwater flow. A detailed presentation of the model can be found in Bouraoui et al. (1996). The most important aspects are summarized here and a flow chart showing the major processes simulated and their interactions is presented in Fig. 1.

![Flow chart for the ANSWERS model](image-url)
Infiltration is simulated using the physically-based Green-Ampt equation (Green & Ampt, 1911). The infiltration process is represented as a saturated wetting front travelling down the soil profile. The soil moisture behind the wetting front is at saturation, while ahead of the wetting front the soil moisture is equal to the antecedent soil moisture. The basic Green-Ampt equation to compute cumulative infiltration is:

\[ K_t = I - N_s \ln \left( 1 + \frac{1}{N_s} \right) \]  

where \( K_s \) (cm h\(^{-1}\)) is the saturated hydraulic conductivity, \( I \) is cumulative infiltration (cm), \( t \) is time (h\(^{-1}\)) and \( N_s \) (cm) is the product of the suction at the wetting front and the available porosity. The modifications proposed by Mein & Larson (1972) were used to consider infiltration under un-ponded conditions.

At the end of the rainstorm, and between storm events, soil water redistribution is computed based on the assumption of a gravity flow under unsaturated conditions. Travel time of percolating water through the soil matrix is regulated by the unsaturated hydraulic conductivity which is determined by the Brooks & Corey (1964) equation, using the method developed by Haverkamp & Parlange (1986). All the surface excess water can be routed to the channel network and then to the drainage basin outlet with the use of Manning’s equation.

It is assumed that there is no lateral subsurface flow from one cell to another in the unsaturated zone. Thus, the unique recharge of an aquifer cell is the excess water draining from the corresponding overlying cells. The draining water is added to the groundwater volume present in each aquifer cell. An average daily value of aquifer discharge is computed at the downstream limit using a Darcy type equation, and a new piezometric head is determined by mass balance. The model relies on an extensive soil data base, including density, grain size distribution and organic matter content, to determine the transport coefficients being used to simulate water transport in the soil from pedotransfer functions (Rawls & Brakensiek, 1989).

The ANSWERS model represents plant growth by a time varying leaf area index (LAI). For each crop cover, idealized values of the LAI (Knisel, 1980) are used as input to the model for ten stages of the plant growth. A linear interpolation is made on a daily base for each growth stage. The root depth, which determines the extent of the root zone and the amount of water available for transpiration, is computed daily (Borg et al., 1986). Evapotranspiration is determined based on Ritchie’s approach (Ritchie, 1972). The daily value of LAI is used to partition potential evapotranspiration into potential soil evaporation and potential plant transpiration.

**EXPERIMENTAL LAYOUT AND DATA DESCRIPTION**

The site selected for the calibration and validation is "La Côte St André", 60 km north-east of Grenoble (southeast France). The basin is about 500 km\(^2\) and the elevation varies from 480 to 250 m. Three different sets of data are considered: soil, vegetation (crop cover and management practices) and aquifer data. The major part of the basin (about 80%) is a flat plain with very permeable, fertile, unconsolidated soil which is surrounded by hills, with an average slope of 7.7%. Hills are covered with grass and forest;
the plain is cultivated either with irrigated maize and tobacco (30% of the area) or with dry farming crops such as sunflower and corn.

The groundwater holding layer consists of very coarse glacial materials of average thickness of 20-30 m, with a water table aquifer. The aquifer is characterized by very high transmissivities (range from $5 \times 10^{-2}$ to $10^{-1}$ m$^2$ s$^{-1}$) and high velocities (between 5 and 10 m per day). The effective porosity of the aquifer is about 10%, and its depth fluctuates around 5 m during a year, with a typical range of average depth of 10-15 m below the soil surface. The changes of piezometric levels may be very fast during the rain season. Weekly measurements of the piezometric level are available for five different wells (wells 1-5). The annual precipitation was 788, 952 and 1172 mm for 1991, 1992 and 1993, respectively. The corresponding annual potential evapotranspiration values were 795, 717 and 737 mm.

**LINKAGE WITH A GEOGRAPHICAL INFORMATION SYSTEM**

The model has been linked with GRASS (Geographical Resources Analysis and Support System; US Army Corps of Engineers, 1993), a raster based geographic information system (GIS). This linkage allows the automation of the input file creation, and the easy modification and manipulation of the cell size and its associated geo-referenced data. It also plays an important role in input and output data visualization. The coupling of the ANSWERS model with the GIS is illustrated in Fig. 1. The data layers required by the model include soil, vegetation and aquifer characteristics.

**Soil map**

A digitized soil map of the area was reclassified into clay, sand and organic matter content maps. A textural map of the top horizon is shown in Fig. 2. A bulk density map was generated from the three previous maps, using the statistical regression function developed by Rawls & Brakensiek (1989). These four maps constitute the basis for
determining the hydrodynamic parameters of the soils, i.e. the saturated hydraulic conductivity (Fig. 3) and the suction at the wetting front (Rawls & Brakensiek, 1989).

**Vegetation map**

A vegetation map, including land use (soil occupation and rotation) and irrigation areas is shown in Fig. 4. This map was used along with a data base of plant characteristics to estimate daily plant growth. This information was used to estimate interception and evapotranspiration.

**Digital elevation model and aquifer characteristics**

A digital elevation model (DEM) at 50 m resolution was used to determine the elevation for each grid point of the drainage basin. The DEM was also used to determine the
hydrological catchment properties, in particular the drainage basin delineation, the slope and the flow direction, parameters used by the model to compute runoff. A map of the bedrock elevation was kriged using 100 points determined from geophysical profiles. A piezometric map was kriged using 78 well measurements done on 7 January 1991. Then the topographic map and the piezometric map were combined (subtracted) to determine the initial thickness of the unsaturated zone. In a similar manner, the piezometric and the bedrock elevation maps were combined to obtain a map of the aquifer thickness.

VALIDATION

The model was applied to the entire plain to test its ability to predict the recharge of the aquifer as influenced by the surface cover management and soil depth to the aquifer. The soil was discretized into three layers. Two layers were used to simulate the root zone, the third layer extended from below the root zone to the top of the aquifer. The surrounding boundary conditions for the aquifer were assumed to be a no flow boundary condition. The cell size was optimized to limit the amount of calculation and to capture the spatial variability of soil properties and land use; the drainage basin was thus discretized into 1 ha cells. It is important to note that due to the high infiltrability of the top soil, no noticeable runoff events occurred during the simulation period. Thus there will be no mention to runoff in the following discussion.

The first 6 months of the data set was used for calibration, and the model was then run for 30 months. The calibration consisted in adjusting the hydraulic conductivity (travel time) of the third layer until the predicted water level fluctuations matched those measured on the different validation wells. The prediction for the water level is given in Fig. 5 for one of the validation well (well 1). The model reproduces well the variations of the water table level, and particularly the high level of water during winter and early spring when the soil is completely bare (Fig. 5). The model also predicts that no significant rise of the aquifer level will occur during the summer. This is mainly due

![Fig. 5 Predicted and measured piezometric level for validation well 1 (a.m.s.l.).](image-url)
to the presence of maize, a highly transpiring plant which limits the amount of deep percolation. Thus, during these periods of no deep percolation, there will be no leaching of nitrate. The quick rise of the water level occurring from October to December 1993
after very important rain occurrence in September (500 mm or about one half of the annual rainfall) is reproduced well. Similar results were observed on the four other validation wells (Fig. 6).

The model was shown to be very responsive to different land use cover and the model predicted well, at the local scale, the influence of management practices on the water balance (Bouraoui et al., 1996). The influence of vegetation on groundwater recharge can be observed in Fig. 7 where the cumulated drainage of irrigated corn is lower than that of grassland. This difference in cumulative drainage occurs during the corn growing season when evaporative demand of the corn is much higher than that of the grassland.

Acknowledgement This work was funded by the commission of European Community, DGXII, Research Contract EV5V-CT94-0484, and by the CNRS (Centre National de la Recherche Scientifique, Paris), Programme Environnement, Vie, Société and Programme de Recherche en Hydrologie.

REFERENCES


