INTEGRATING SYSTEM MODELING WITH FIELD RESEARCH IN AGRICULTURE: APPLICATIONS OF THE ROOT ZONE WATER QUALITY MODEL (RZWQM)

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I. INTRODUCTION

Process-level models are a synthesis and quantification of knowledge gained from years of research and experience. They represent our current understanding of the physical, chemical, and biological processes, and their interactions are based on fundamental principles that govern all natural systems. Obviously, modeling should be an integral part of all new laboratory and field research to advance knowledge and technology. There are numerous examples of the interactive use of models with experimentation to advance knowledge most efficiently, such as in space and nuclear sciences. We would not have gone to the Moon without the use of models and good data, working together. Likewise, the EPA (Environmental Protection Agency) will not authorize a major waste- (e.g., nuclear waste) disposal project without safety and feasibility analyses of the project using models.

The field research in agriculture has so far been largely empirical and site specific and conducted without active help of agricultural system models. There is no doubt that this type of research has advanced our understanding of many components in an agricultural system, albeit on a piecemeal basis. However, as we enter the 21st century, agricultural research will have more difficult and complex problems to solve and to do this with limited funding. It will also have to absorb and make sense of the information overload, brought in by the Internet, remote sensing, improved weather forecasting, and other means. Our customers are asking us to do a better job in transferring research results to them quickly and in an integrated form, at the whole-system level, to help them improve their management. Time is, therefore, ripe to start integrating whole-system modeling with field research in agriculture. This integration will make field research easier to interpret and more quantitative and focused on critical knowledge gaps. Field research will not be complete unless the results are analyzed and interpreted with a system approach. In return, the models will be gradually improved with this interaction.

Models provide a ready means of translating research to other locations and thus minimize duplication of field research. They will also provide a ready means to transfer the integrated knowledge and technology to farmers and other users. Models will be the only way to cut through the information overload of the 21st century. In response to these needs, several agricultural system models have been developed. Examples of these models are GLEAMS (Groundwater Loading Effects of Agricultural Management Systems) (Leonard *et al.*, 1987), CERES (Hanks and Ritchie, 1991), CENTURY (Parton *et al.*, 1994), DSSAT (Decision Support

System for Agrotechnology Transfer) (Tsuji *et al.*, 1998), RZWQM (Root Zone Water Quality Model) (Ahuja *et al.*, 1999a), GPFARM (Great Plains Framework for Agricultural Resources Management) (Ascough *et al.*, 1998), ECOSYS (Grant, 1995a,b), Opus (Smith, 1990), EPIC (Erosion Productivity Impact Calculator) (Sharpley and Williams, 1993), and SPUR (Simulation of Production and Utilization of Rangelands) (Foy *et al.*, 1999). Although these models are far from perfect and need to be tested and improved more thoroughly across time and space, they have brought the sense of system approach to the agricultural science community and new understandings to agricultural systems.

In this chapter, we focus on RZWQM as an example. RZWQM is an agricultural system model developed over the past 12 years by USDA-ARS, Great Plains Systems Research Unit in Fort Collins in cooperation with several other scientists. It integrates the state-of-the-science knowledge of agricultural systems into a tool for agricultural research and management, environmental assessment, and technology transfer. It has been evaluated during the Management Systems Evaluation Areas (MSEA) projects in several midwestern states of the United States (Iowa, Missouri, Minnesota, Nebraska, and Ohio). Model evaluation was also performed in Illinois, Arkansas, Colorado, Georgia, and North Carolina and in other countries, such as Canada, Portugal, Germany, and The Netherlands. A technical documentation and the model were published by Water Resources Publications, LLC., and contain the RZWQM Window95/98/NT user interface (RZWQM98) (Ahuja *et al.*, 1999a; Rojas *et al.*, 1999).

Major components of RZWQM have performed satisfactorily, although further evaluations under different conditions are desirable. These components are water movement (Ahuja *et al.*, 1993, 1995), pesticide transport (Ahuja *et al.*, 1993, 1996; Ma *et al.*, 1995, 1996), evapotranspiration (Farahani and Bausch, 1995; Farahani and Ahuja, 1996), subsurface tile drainage (Johnsen *et al.*, 1995; Singh and Kanwar, 1995a,b), organic matter/nitrogen cycling (Hansen *et al.*, 1995; Ma *et al.*, 1998a,b), plant growth (Nokes *et al.*, 1996; Ma *et al.*, 2000a; Nielsen *et al.*, 2000), and agricultural management (Ahuja *et al.*, 1998b; Singh and Kanwar, 1995b; Ma *et al.*, 1998a,b). These evaluations contributed much to our understanding of agricultural systems and associated environmental problems, with more than 90 publications in the literature.

Evaluation of RZWQM is a continuous process and the model has many refinements since it was released for its application in the MSEA projects. Examples of these refinements include tillage effects on hydraulic properties (Ahuja *et al.*, 1998a), manure management (Ma *et al.*, 1998a,b), crop yield response to water stress (Ma *et al.*, 2000a; Nielsen *et al.*, 2000), relationship between canopy resistance and leaf area index (Cameira, 1999), and pesticide transport (Wauchope *et al.*, 1999). Along with numerous improvements in computation techniques, these refinements have brought new features to the model and improved the science in the model. Therefore, the conclusions drawn from some of the early applications in the literature may not be strictly valid and these conclusions may not be cited as typical behavior of the current model. For example, although the set of MSEA papers was published recently (Watts *et al.*, 1999), all the applications used the earliest version of RZWQM released in 1992. The now more complete MSEA data sets are reexamined with the newest version of RZWQM.

Recently, the environmental aspects of RZWQM application have been highlighted (Ma *et al.*, 1998c; Ahuja *et al.*, 1998b; Malone *et al.*, 1999). However, a comprehensive review of RZWQM applications in agricultural research is not available. The objective of this chapter is to summarize RZWQM applications in order to demonstrate the use of models in field research within the context of a whole system and to further understand the complex interactions within agricultural systems.

II. RZWQM DESCRIPTION

RZWQM consists of six subsystems or processes that represent a complete agricultural system. Each subsystem has been illustrated in detail in the RZWQM technical documentation (Ahuja *et al.*, 1999a) and in other publications (RZWQM Team, 1998; Ahuja *et al.*, 1998b). In general, RZWQM is an integrated physical, biological, and chemical process model that simulates plant growth and movement of water, nutrients, and pesticides over and through the root zone at a representative area of an agricultural cropping system. It is a one-dimensional (vertical into the soil profile) model designed to simulate conditions on a unit-area basis. Although the principal zone of focus is the crop root zone, the model can be extended to the deeper vadose zone.

The model allows simulation of a wide spectrum of management practices and scenarios. These management alternatives include evaluation of conservation tillage and residue cover versus conventional tillage, methods and timing of fertilizer and pesticide applications, manure and alternative chemical formulations, irrigation and drainage technology, methods and timing of water applications, and different crop rotations. The model contains special features such as the rapid transport of surface-applied chemicals through macropores to deeper depths and the preferential transport of chemicals within the soil matrix via mobile–immobile zones. The transfer of surface-applied chemicals to runoff water is also an important component.

The model's generic crop-growth component plays a major role in effecting the state of the simulation system. Shading from the plant canopy reduces soil evaporation, while transpiration drives uptake of soil water and nutrients from the soil by plant roots. Seasonal sloughing of leaf material and dead roots along with harvest residue provide a source of carbon and nitrogen for the soil nutrient transformations. Estimates of crop production and yield allow for a relative economic evaluation of the simulation results.

The chemical system within the soil matrix features a complete interaction between nutrient transformations and equilibrium soil chemistry. These two processes characterize soil pH and chemical state of the soil. A multipool system of soil organic carbon forms the core of the nutrient transformation system. Microorganism populations respond to the supply of food sources, environmental conditions, and chemical constraints. Chemical equilibrium concentrations of the major ions in the soil solution and on the exchange complex are modified by soil moisture changes, temperature fluctuations, tillage, and bioincorporation of crop residue and manure.

The physically based nature of RZWQM necessitates a good deal of data from the user to adequately parameterize and initialize the model. From experience, users do not have enough data to completely describe the state of an agricultural cropping system. Thus, to facilitate use of the model, RZWQM allows for input options where certain parameters are estimated or obtained from default value tables. A list of the minimum data required to run the model is given in Table I. A simplification of the execution sequence for RZWQM shows the relative flow of information between all the major components of the model (Fig. 1). The two time

Table I

Minimum Data Required to Run RZWQM[a]

Data type	Minimum data required
Breakpoint rainfall	Breakpoint rainfall data with a minimum of two pairs of rainfall amounts and times
Daily meteorology	Daily meteorology data (minimum and maximum air temperature, wind ran, solar radiation, and relative humidity)
Site description	Soil horizon delineation by depth
	Soil horizon physical properties—Bulk density and particle size fractions for each horizon
	Optional—Soil horizon hydraulic properties: 330- or 100-cm-suction water content and saturated hydraulic conductivity if available for each horizon
	Estimate of dry mass and age of residue on the surface
	General pesticide data such as common name, half-life, K_{oc}^{b}, dissipation pathway (this information can be found in the ARS pesticide database)
	Specifying a crop from supplied database with regional parameters
	Management selections and additions as needed
Initial state	Initial soil moisture contents
	Initial soil temperatures
	Initial soil pH and CEC (cation exchange capacity) values
	Initial nutrient model inputs (soil residue, humus, microbial populations, mineral NO_3-N, NH_4-N—Use RZWQM98 wizards to determine).

[a] After Ahuja *et al.* (1999c).

[b] Soil organic carbon based adsorption coefficient.

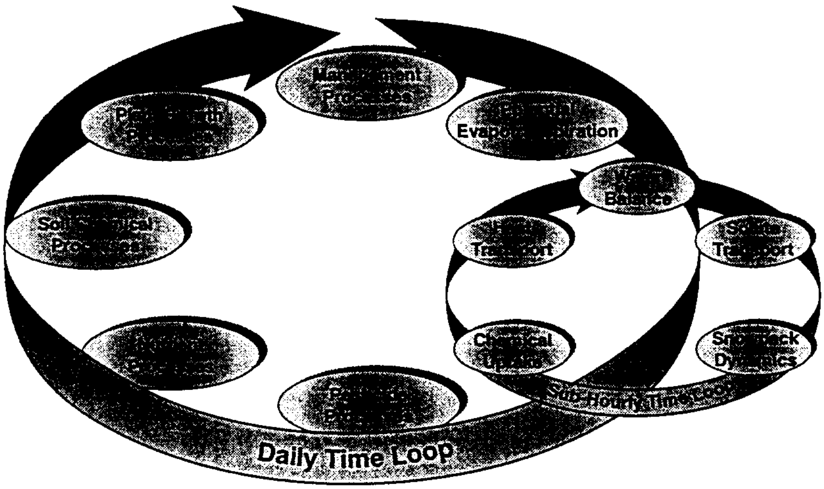


Figure 1 Execution sequence of components in RZWQM (after Ahuja *et al.*, 1999c).

scales are represented by the two looping arrows. The larger loop is the daily time scale and the smaller loop is the subhourly time scale. The subhourly time-scale calculations are performed within the daily time-scale sequence.

Management effects (of tillage and the addition of manures, chemicals, or irrigation water) on the system are calculated first. A daily estimate of potential evapotranspiration is then determined so that the evaporation and transpiration fluxes can be applied to the soil surface and plant roots, respectively. The subhourly time loop is then executed to calculate water, chemical, and heat transport and associated exchanges. The processes include infiltration and runoff, soil water distribution, chemical transport, pesticide washoff, heat movement, actual evaporation and transpiration, plant nitrogen uptake, reconsolidation of tilled soil, and snowpack dynamics.

Continuing along the daily loop, pesticides degrade on plant and residue surfaces and within soil layers. Pools of carbon and nitrogen are transformed by the nutrient processes. The soil chemical processes determine pH and salinity. Finally, after accounting for all the physical and chemical changes to the system throughout the day, the plant growth processes determine crop production.

A. Physical Processes

Physical processes include a number of interrelated hydrologic processes—rain or irrigation water infiltration through soil matrix and macropores; transfer of chemicals from surface soil to runoff; chemical transport during infiltration; redistribution of soil water and chemicals after infiltration; plant water uptake and evaporation; and heat transport and soil temperature changes during infiltration, redistribution, and snow accumulation and melt. The transport of up to three different pesticides, nitrate, and several other water-soluble chemicals is handled simultaneously. Freezing and thawing of soil is not done at present, but will be added soon. Soil erosion and the overland routing of runoff and erosion to an outlet is included as an optional test module.

The infiltration of water into the soil matrix, which may be layered and may have a surface crust, is simulated by a modified Green–Ampt approach (Ahuja *et al.*, 1993, 1995). The rainfall excess or overland flow enters the macropores open to the surface (if present) and is subject to lateral infiltration into the soil matrix below the vertical wetting front. Chemical transfer to overland flow is modeled by a nonuniform mixing approach. Chemical transport in the matrix uses a partial-piston displacement, partial-mixing approach applied to 1-cm-deep increments during infiltration and to coarser increments during redistribution. The redistribution of soil water, including plant uptake and surface evaporation, is simulated by a mass-conservative numerical solution of the Richards' equation. Fluctuating water table and tile flow are a part of this solution (Johnsen *et al.*, 1995). Potential evaporation and transpiration rates are estimated by a revised form of the (Shuttleworth and Wallace, 1985) double-layer model that uses relevant climatic data to partition potential evapotranspiration from a soil-residue-canopy system into (a) evaporation from bare soil and the residue-covered soil and (b) crop transpiration (Farahani and Bausch, 1995; Farahani and Ahuja, 1996). Parameters associated with the ET module are detailed by Farahani and DeCoursey (1999). Heat transport involves an advective displacement during infiltration, like in chemical transport, and a numerical solution of the diffusion–advection during redistribution that is linked to water movement. Pesticide transport in soil and runoff is based on either an instantaneous equilibrium sorption or a two-site model in which some of the sorption sites undergo first-order kinetics (Ma *et al.*, 1996). The overland flow and soil erosion and their routing, as well as snow accumulation and melt, are as described in the PRMS model (Leavesley *et al.*, 1983).

Soil hydraulic properties (water retention curve and hydraulic conductivity) are estimated from soil bulk density, texture, and, if available, soil water content at 333- or 100-cm suction head (Rawls *et al.*, 1982; Ahuja *et al.*, 1989, 1999b). Also, users can specify measured hydraulic properties as parameters necessary to describe the Brooks–Corey relationships. Surface crust effect on infiltration is simulated by assuming a soil layer with lower hydraulic conductivity located above the surface layer (Ahuja, 1983). Chemical loss to surface runoff is estimated from the amount of chemicals extracted from the surface soil (Ahuja, 1986).

B. Soil Chemical Processes

The soil inorganic chemical environment simulated in support of nutrient processes, chemical transport, and pesticide processes includes bicarbonate buffering;

dissolution and precipitation of calcium carbonate, gypsum, and aluminum hydroxide; ion exchange involving bases and aluminum; and solution chemistry of ion complexes (Shaffer *et al.*, 1999a). The chemical state is characterized by soil pH, solution concentrations of major ions, and ions adsorbed on the exchange complex. The above simulations utilize the well-established chemical equilibrium equations, which are solved simultaneously using the Newton–Raphson approach. The combination of equilibrium equations varies with the current pH of the system.

C. Nutrient Processes

The nutrient process submodel, OMNI (Organic Matter/Nitrogen), simulates carbon and nitrogen transformations within the soil profile (Shaffer *et al.*, 1999b). Given initial levels of soil humus; manure; crop residues; soil microbial populations; and nitrate (NO_3-N), ammonium (NH_4-N), and urea concentrations, the model calculates volatilization, nitrification, immobilization, and denitrification of nitrogen. Soil organic matter is distributed over five computational pools and is decomposed by three types of microbial populations. The five OM pools include the fast and slow pools for crop residues and other organic amendments (e.g., manure) and the fast-, intermediate-, and slow-decaying soil organic matter pools. Organic carbon in each pool may be transferred to other pools (interpool transfer), given off as CO_2 or CH_4, or assimilated into microbial biomass. The three microbial populations are aerobic heterotrophs, autotrophs (nitrifiers), and anaerobic heterotrophs. Process-rate equations for each pool are based on zero or first-order chemical kinetics and controlled by microbial population size and environmental variables of soil temperature, water content, pH, nutrients, and salinity. Levels of soluble nutrients are used in estimating crop uptake, leaching from the root zone, and concentrations in runoff.

Surface-applied manure and crop residues are partitioned into the fast and slow residue pools by means of tillage and fauna activity (Ma *et al.*, 1998a,b). Parameters associated with OMNI have been calibrated in previous publications (Shaffer *et al.*, 1999b; Hansen *et al.*, 1995; Ma *et al.*, 1998a,b). Since the C/N cycling is dynamic and history dependent, it is essential to initialize the five OM pools and the three microbial pools with respect to past management practices. Currently, these pools are initialized by running the model for 10–15 simulation years prior to the desired simulation period (Ma *et al.*, 1998a,b). Ma *et al.* (1998a) parameterized the intrapool transfer coefficients through calibrating corn yield and crop N uptake in a manure study in Colorado. Jaynes and Miller (1999), on the other hand, adjusted these intrapool transfer coefficients by assuming that total soil organic matter content remains stable and should be equal to the measured organic matter content in soils under consistent long term management.

D. Plant Growth Processes

The generic plant-growth and crop-production submodel contains population development, plant-growth, and environmental fitness components (Hanson, 1999). The population dynamics are simulated using a modified Leslie-matrix model, assuming a population life-history can be divided into a given number of discrete classes, with each class having a class-specific fecundity rate and a probability of surviving to the next age class. The plant-growth component tracks carbon and nitrogen throughout the plant. The processes include photosynthesis, nitrogen uptake, carbon and nitrogen partitioning, root growth, respiration, and mortality. The allocable carbon is partitioned between leaves, stems, roots, and reproductive organs based on the plant growth stage and growth demand of each tissue type. Viable seeds are produced from propagules. The "environmental fitness" of the system to obtain healthy plant growth and population development is a function of temperature, soil water availability, and plant nutrient status. Factors for each of these fitness parameters are determined on a scale from 0 (fully stressful) to 1 (optimal for plant production). These factors are then combined to determine the overall environmental fitness for the plant under the present conditions. Plant development is expressed in terms of growth stage index scaled between 0 and 1. Under perfect environmental conditions, a minimum amount of time is required for a plant to move from one phenological stage to the next. The rate of passage between these stages can be reduced according to the environmental fitness.

Plant photosynthesis is simulated with a rectangular hyperbola equation (Hanson, 1991), and whole plant photorespiration is estimated from the respiration quotient of the plant (Q_{10}) (McCree, 1970). The model assumes that 25% of the photosynthate after photorespiration is required for general plant maintenance. Carbon partitioning among plant organs is a function of growth stage (scaled from 0 to 1) (Hanson, 1999). Up to 50% of above-ground biomass can die during a day under severe environmental stresses. Root growth in response to soil temperature, soil moisture, soil aeration, and calcium and aluminum concentrations is simulated using the methods of CERES-Maize (Jones *et al.*, 1991). Currently the plant growth parameters were obtained from the MSEA projects. The parameters for corn were calibrated in Colorado, Iowa, Minnesota, Nebraska, and Ohio, whereas those for soybean were from testing in Colorado, Minnesota, Missouri, and Ohio (Hanson, 1999). All other simulations of plant growth are based on these derived parameters. Parameters for other crops are being developed.

E. Pesticide Processes

Pesticide processes include the degradation and washoff of pesticides applied to plant surfaces, crop residue surfaces, the soil surface, and within each soil layer

(Ma *et al.*, 1996; Wauchope *et al.*, 1999). Pesticide uptake by plants is not considered, however. Depending upon the application site and given the plant, residue, soil, and pesticide characteristics and environmental conditions (e.g., temperature and soil moisture), the model simulates the degradation and the amount either adsorbed or mobile. The degradation is typically modeled as lumped first-order kinetics. In addition to this lumped degradation, separate dissipation pathways of volatilization, photolysis, hydrolysis, anaerobic and aerobic biodegradation, oxidation, and complex are provided if input data are available to drive them. Finally, a mechanism for daughter-product formation and degradation is also provided if input data are available. Equilibrium and kinetic adsorption/desorption are used to obtain a balance between adsorbed and solution phase of each pesticide. Pesticide washoff from plant and residue surfaces is simulated by empirical first-order equations, whereas a nonuniform mixing approach is used for pesticides in runoff water.

The pesticide submodel has been rewritten by Wauchope *et al.* (1999). A pesticide database complied by Wauchope *et al.* (1992) and Hornsby *et al.* (1996) is used in the RZWQM. The database contains values for half-life, molecular weight, vapor pressure, Henry's law constant, octanol/water partition coefficient, and soil organic carbon sorption constant. Foliar washoff parameters are based on the work of Willis and coworkers (e.g., Willis *et al.*, 1992, 1994) and pesticide solubility in water (Wauchope *et al.*, 1999).

F. Agricultural Management Processes

RZWQM has the capability of handling crop rotations; tillage operations; irrigation; and fertilizer, pesticide, and manure applications (Rojas and Ahuja, 1999). Crop planting and harvesting are scheduled by the user and crop residues are returned to the soil surface if desired. Surface residue decomposition is based on the work of Douglas and Rickman (1992). Tillage operations modify soil bulk density and residue pools (Williams *et al.*, 1984). Tillage and reconsolidation of soil after tillage is modeled by the method of Linden and van Doren (1987). Tillage effects on soil hydraulic properties are estimated from Ahuja *et al.* (1998b). Application efficiencies of water, fertilizer, and manure are 100%, while the efficiency of pesticide applications depends on application methods (Wauchope *et al.*, 1999).

Fertilizer and manure can be left on the surface, incorporated, injected, or fertigated. RZWQM handles different application timings as well as automatically schedules an event based on leaf N content. Water irrigation may be applied by sprinkler, flood, or drip methods. Timing of irrigation can be fixed interval, specific dates, or connected to soil water depletion. Crops may be harvested on a specific day or at a specific growth stage. Harvest options include multiple or single harvests of seed, above-ground biomass, or root (Rojas and Ahuja, 1999).

G. Graphical User Interface

To enhance user utility when working with RZWQM, the simulation model is encapsulated within a Windows95/98/NT shell. This system (RZWQM98) facilitates entering input data, determining site-specific parameters, establishing the initial state, and displaying graphs of simulation results. For input data, help is provided through databases for soil descriptions, pesticide properties, crop growth, and management scenarios. A weather generator (CLIGEN) is included to help produce daily meteorology data and rainstorms from daily rainfall data where observations are not available (Rojas *et al.*, 1999).

III. MODEL CALIBRATION AND PARAMETERIZATION

Generally, the model is calibrated for water balance first, then organic matter/ microorganism pools, and, last, plant growth (Hanson *et al.*, 1999; Ma *et al.*, 1998a). Model parameters that are difficult to measure may be estimated by calibration of simulation results against known data. Not all the parameters are calibrated in RZWQM, as most of the parameters are measured or estimated or use default values. Soil hydraulic properties are generally obtained from site-specific measurements (Ma *et al.*, 1998b; Ahuja *et al.*, 1995; Martin and Watts, 1999; Jaynes and Miller, 1999) or estimated by the model from limited data (Ma *et al.*, 1998a, 2000a). If necessary, they may be further calibrated from soil water movement (Singh *et al.*, 1996; Ghidey *et al.*, 1999). Organic matter pools are best initialized by running the model for 10 or more simulation years prior to the desired simulation period (Ma *et al.*, 1998a), starting with values estimated from measured potential mineralizable soil N (Landa *et al.*, 1999) or best estimates based on experience. Parameters related to carbon/nitrogen cycling may be calibrated through a comparison of crop yield (Ma *et al.*, 1998a), nitrate in soil or soil solution (Kumar *et al.*, 1998a), and soil organic matter content (Jaynes and Miller, 1999). User adjustable plant growth parameters are maximum nitrogen uptake rate, proportion of photosynthate used for plant maintenance, conversion factor from biomass to leaf-area index (CONVLA), photosynthesis reduction at propagule stage, photosynthesis reduction at seed production stage, and maximum rooting depth (Hanson *et al.*, 1999). In several MSEA site studies, CONVLA was shown to be the most sensitive parameter and much of the calibration for plant growth was done using that parameter (Hanson *et al.*, 1999; Ghidey *et al.*, 1999; Martin and Watts, 1999). Besides model parameters, initial conditions may also need to be calibrated when they are unknown (Singh *et al.*, 1996; Singh and Kanwar, 1995a,b). Due to spatial and temporal variability, some of the point-measured values may require adjustment to represent a field, such as soil horizon depth

(Martin and Watts, 1999), 33-kPa water content (Singh *et al.*, 1996), macroporosity (Singh and Kanwar, 1995a), depth of tile drain to impermeable layer (Singh and Kanwar, 1995a), and pesticide adsorption constant (Ma *et al.*, 1996; Jaynes and Miller, 1999).

RZWQM is typically calibrated for 1 year and then tested for other years (Hanson *et al.*, 1999; Singh *et al.*, 1996; Ma *et al.*, 1998a; Ghidey *et al.*, 1999). It has also been calibrated on one soil topographic site (Farahani *et al.*, 1999, 1995), or for one type of agricultural management (Ma *et al.*, 1998a; Martin and Watts, 1999), and then tested for others. Depending on the purpose of model application, some of the processes in RZWQM may be replaced with experimental measurements, for example, actual plant growth data may be used instead of simulating plant growth (Ma *et al.*, 1998b).

The goodness-of-model calibration depends on experimental conditions and data availability. Calibrated errors can vary from 5% (Farahani *et al.*, 1999; Jaynes and Miller, 1999) to 10% (Ghidey *et al.*, 1999; Singh *et al.*, 1996), 15% (Hanson *et al.*, 1999), and 20% (Singh and Kanwar, 1995a,b). RZWQM seldom provides equally good descriptions for all experimental data or processes. Nokes *et al.* (1996) found that corn yield was better simulated than leaf and stem biomass. Ma *et al.* (1998b) obtained better description of soil profile nitrate than nitrate concentration in suction lysimeters. Jaynes and Miller (1999) were able to obtain good values for total nitrate in the soil profile and nitrate leaching at the Iowa MSEA site, but nitrate distribution in the soil profile was not well reproduced. Some investigations have used simple criteria in evaluating RZWQM, such as maximum penetration depth of pesticide, center of mass, range of agrichemical concentrations (maximum error) in the soil profile, and general responses to agricultural management (Azevedo *et al.*, 1997a; Singh and Kanwar, 1995b; Ma *et al.*, 1998b; Martin and Watts, 1999; Cook, 1996).

IV. MODEL SENSITIVITY ANALYSIS

Sensitivity analysis of RZWQM helps identify key parameters for calibration and evaluation of model response to different agricultural management practices (Walker, 1996). Singh *et al.* (1996) identified the most sensitive parameters responsible for subsurface drainage as effective porosity, initial water content, and lateral saturated conductivity (K_{sat}). With calibration of these parameters, Singh and Kanwar (1995a,b) obtained similar response of water movement and nitrate concentration in tile drainage to different tillage systems as observed for the field. Kumar *et al.* (1998b) also found that macropore flow was sensitive to K_{sat} of the surface layer and lateral K_{sat} of macropore walls. Atrazine losses to tile drains were sensitive to macroporosity and lateral adsorption by macropore walls, whereas total subsurface drainage was not sensitive to macroporosity under their experimental set up. Walker (1996) studied the responses of seven model outputs (infiltration, surface runoff, tile flow, evapotranspiration, water flux into ground water, nitrate in tile drainage, and crop yield) to 10 model parameters related to soil hydraulic properties, surface residue, plant growth, nitrogen uptake, nitrification, and denitrification. Sensitivity analysis revealed that tile flow, tile nitrate, and crop yield showed the greatest responses based on a sensitivity index suggested by Nearing *et al.* (1990). As expected, soil hydraulic properties had greatest effect on tile flow and tile nitrate concentration, but they had little effect on crop yield.

Sensitivity analysis can also be used to investigate phenomena that cannot be otherwise studied experimentally. Ahuja *et al.* (1993) found that flow into macropores was not very sensitive to macropore size, which makes the determination of macropore size not critical in predicting chemical distribution in the macroporous soil. A similar effect was obtained for pesticide transport (Ellerbroek *et al.*, 1998). Ahuja *et al.* (1993) also compared the role of evaporation and transpiration on chemical transport through macropores and the soil matrix. They found that evaporation increased the amount of chemicals transported in macropores, but decreased their downward movement through the soil matrix. On the other hand, transpiration (water uptake by roots) decreased both the amount of chemicals entering the macropores and the movement in the soil matrix. Ellerbroek *et al.* (1998) applied a modified Monte Carlo method (Latin Hypercube Sampling method) to study the effects of spatial variabilities of hydraulic conductivity and irrigation water on metolachlor transport into groundwater. They found that varying irrigation water had the most significant effects on metolachlor transport and saturated hydraulic conductivity affected metolachlor transport only at high water-application rates. They concluded that variability in agricultural management (extrinsic variability) had a greater impact than intrinsic variability (saturated hydraulic conductivity).

Azevedo *et al.* (1997b) extended the calibrated RZWQM model of Singh *et al.* (1996) to simulate N management effects on nitrate leaching and corn yield under the moldboard plow and no-till systems using 15-year runs. As expected, RZWQM correctly predicted the increase of nitrate-N losses to drainage flow and corn yield with fertilizer application rate. They also found that RZWQM provided similar simulations of nitrate-N losses and corn yield when fertilizer was applied in a single dose (10 days before planting) or in two split doses (10 days before and 20 days after planting), as predicted by Ma *et al.* (2000c). Since increasing N application from 150 kg/ha to 200 kg/ha doubled N losses in tile drainage but resulted in only 6% increase in yield, the authors recommended 150 kg/ha of N application rate for the corn-belt states. Buchleiter *et al.* (1995) evaluated the effects of 40% overirrigation on crop yield and nitrate leaching after the model was calibrated for a center-pivot-irrigated corn system. They observed an increase of 6.4 cm in water percolate, an increase of 110 kg N/ha of nitrate leaching, and a reduction of 5% in corn biomass. In an irrigated corn study in eastern Colorado, Ma *et al.* (1998a) found that reducing water application to 50% of the normal 20-cm application rate per event significantly decreased water and nitrate leaching beyond the root zone. Although they observed a 13% yield decrease when manure application rate was reduced to 50% (i.e., 22.4 Mg/ha), nitrate leaching was reduced by 46–58%. Ma *et al.* (1998b) found that total soil nitrate content responded well to manure applications, but nitrate concentrations in soil solution did not.

A more recent sensitivity study was conducted to evaluate RZWQM responses (N uptake, silage yield, and NO_3-N leaching beyond the root zone) to key model parameters (Ma *et al.*, 2000b) and to agricultural management practices (Ma *et al.*, 2000c). These studies used the model parameters that were previously calibrated under Colorado conditions (Ma *et al.*, 1998a). In the study of Ma *et al.* (2000b), parameters in four categories (hydraulic properties, carbon/nitrogen cycling, plant growth, and water and manure application rate) were examined for their effects on crop production and water quality. Each parameter was assumed to have a normal or lognormal distribution around the calibrated value. The Latin Hypercube Sampling method was used to sample values from each distribution for simulations (Iman and Shortencarier, 1984). Simulated results (silage yield, NO_3-N leaching, and N uptake) were related to model parameters through linear regression analysis. Coefficients of regression equations were then used as indices of model output sensitivity to the corresponding parameter variables. As shown in Ma *et al.* (2000b), sensitivity of an input parameter depended on the model output selected. Similar to Ellerbroek *et al.* (1998), Ma *et al.* (2000b) found that the model was more sensitive to external changes (water and manure application rates) than to internal variables (e.g., K_{sat}).

The agricultural management practices studied included the methods and rates of water, manure, and fertilizer applications; fertilizer type; tillage; and planting dates (Ma *et al.*, 2000c). Simulation results were generally in agreement with experimental phenomena in the literature (Ma *et al.*, 2000c). Figure 2 shows the responses of model output variables to timing of fertilization (one-time surface NO_3 application) at different growth stages. Early N application increased silage yield and N uptake and decreased N leaching. Significant reduction in silage yield and N uptake was simulated when N was applied 7–11 weeks after planting. Model output responses to planting dates are shown in Fig. 3. Advancing or delaying planting dates decreased silage yield and N uptake, whereas N leaching was increased (Ma *et al.*, 2000c). Although tillage has effects on both soil hydraulic properties and residue incorporation (Ahuja *et al.*, 1999b; Rojas and Ahuja, 1999), its effects on residue incorporation were much greater than on soil hydraulic properties in long-term simulations.

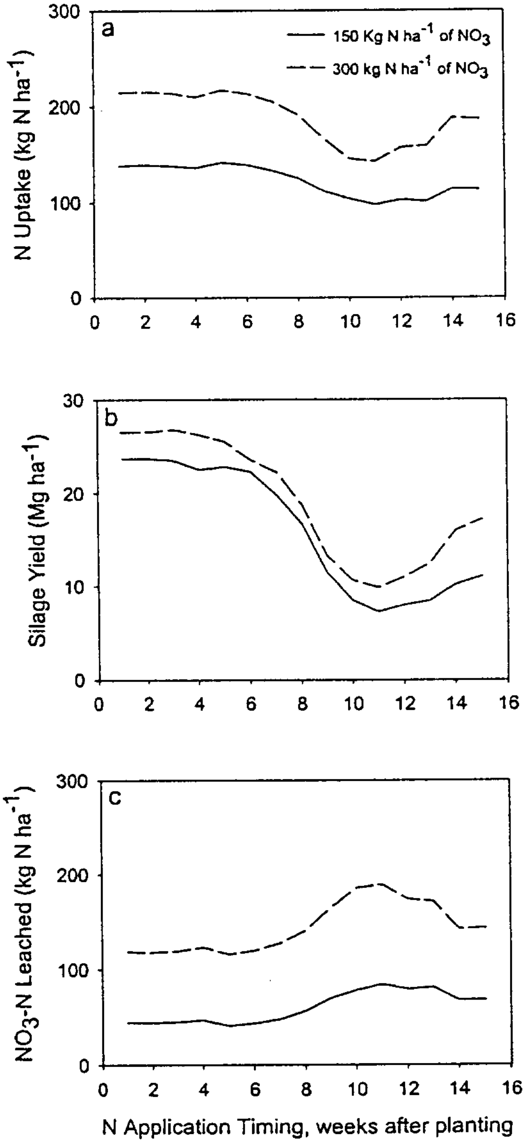


Figure 2 The responses of yearly average plant N uptake (a), silage yield (b), and NO_3-N leaching (c) to N application time in a Colorado corn study. NO_3-N was applied once a year (after Ma *et al.*, 2000c).

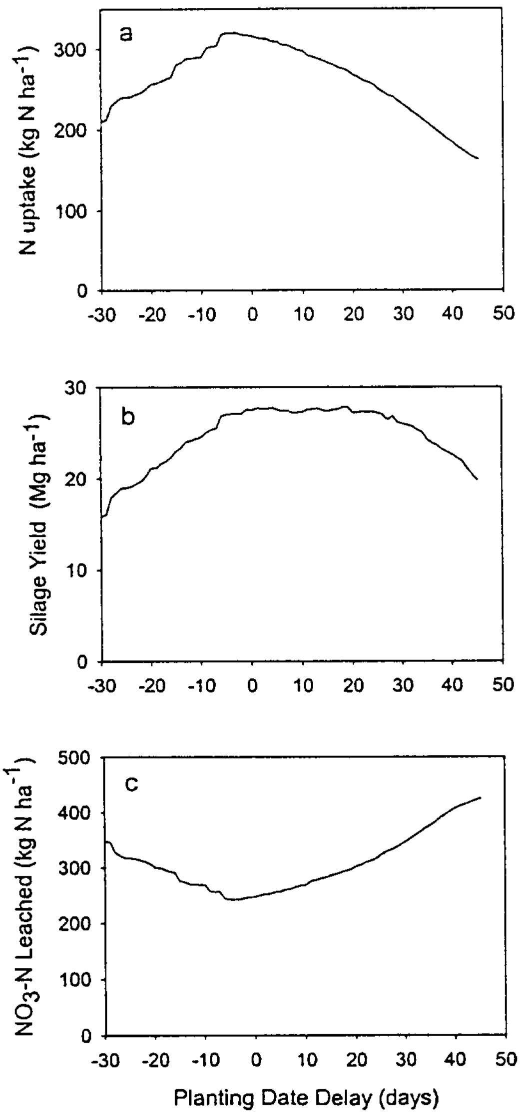


Figure 3 The responses of yearly average plant N uptake (a), silage yield (b), and NO_3-N leaching (c) to planting date in a Colorado corn study (after Ma *et al.*, 2000c).

V. MODEL APPLICATIONS IN FIELD RESEARCH

A. The Weld County, Colorado Study of Manure Management

This study was designed to investigate manure management effects on silage corn production, crop N uptake, and soil N content. The experimental field had a history of beef-manure fertilization every fall after silage corn harvest, without any inorganic fertilizer application. The plots were on a Vona sandy loam. Three plots (15 m by 15 m) were located on the east half and three plots on the west half of the field. The field was irrigated in alternate furrows with ditch water by placing 5-cm-diameter siphon tubes on both the south and north ends of the furrows. The farmer applied approximately 44.8 Mg ha^{-1} beef manure (on a dry-weight basis) to both the west and east sides of the field in the fall of 1993 (mid-October). In the fall of 1994 and 1995, the farmer applied 44.8 Mg ha^{-1} only to the east half of the field, whereas the west half of the field received no manure. Applied manure was incorporated into the soil after 1–2 days with a moldboard plow (Ma *et al.*, 1998a).

RZWQM was extensively calibrated for various organic matter pools based on 1994 and, to a lesser degree, 1995 experimental results by Ma *et al.* (1998a). The soil hydraulic properties were estimated from soil physical properties and measured 33-kPa soil water content. The model adequately simulated silage yield and N uptake for all the 3 years (Fig. 4). Both simulated yield and N uptake were lower than experimental values in 1995, possibly due to inadequate simulation of the model for the wet season in 1995 or to experimental error, since the farmer's overall selling yield was much lower than estimated from sampling blocks. Later refinement on plant responses to water stress in the model has improved the 1995 simulation results (Ma *et al.*, 2000a). Model-simulated soil N concentrations were also close to experimental values (Fig. 5), demonstrating the ability of the model to simulate N soil dynamics under manure management. This study also showed the dynamics of soil organic pools and soil microbial pools and the necessity of stabilizing the pools before RZWQM was used to simulate management effects, especially when N movement and uptake were important.

B. The Akron, Colorado Study of Plant Growth

This study was conducted to evaluate and quantify water stress effects on corn and soybean growth and yield, and selected information is summarized in Table II. The soil type is a Rago silt loam. Corn and soybean were grown under various irrigation water levels. Corn experiments were conducted under a gradient

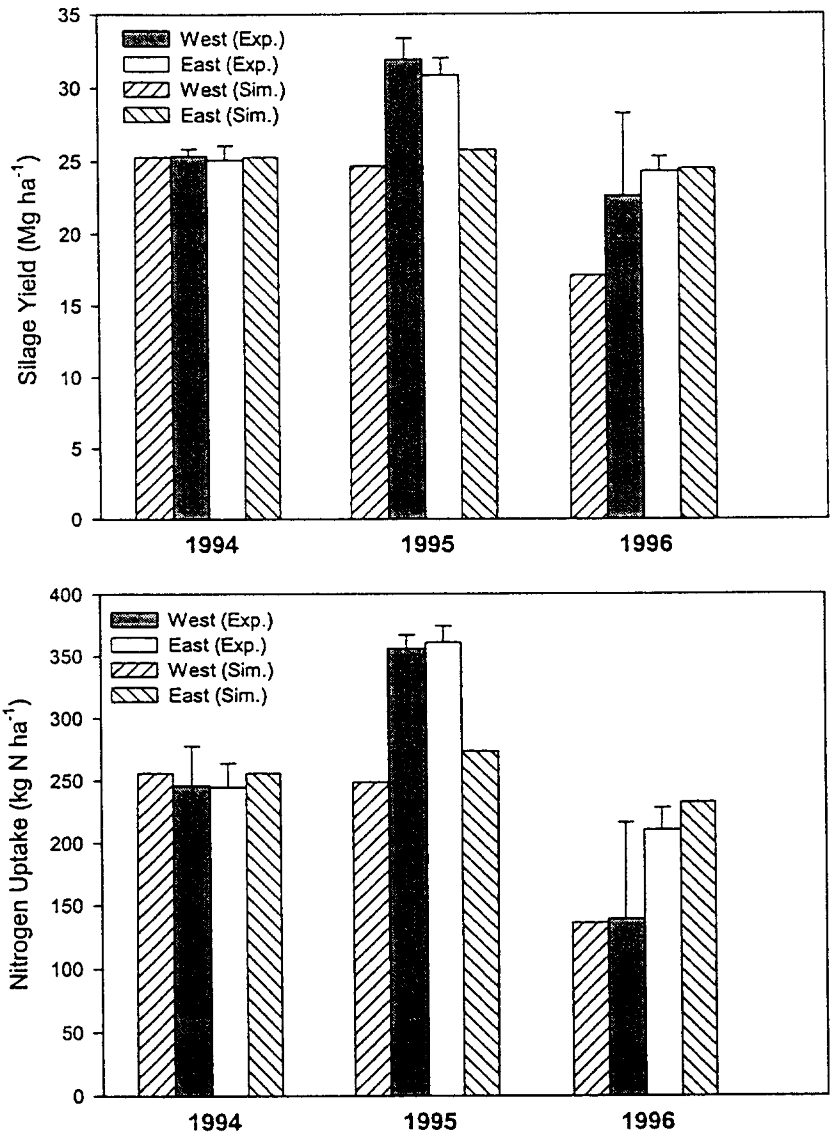


Figure 4 Measured and simulated silage yield and total plant N uptake for the 1994, 1995, and 1996 growing seasons. East site received manure applications in Fall of 1993, 1994, and 1995; west site received manure application in Fall 1993 only (after Ma *et al.*, 1998a).

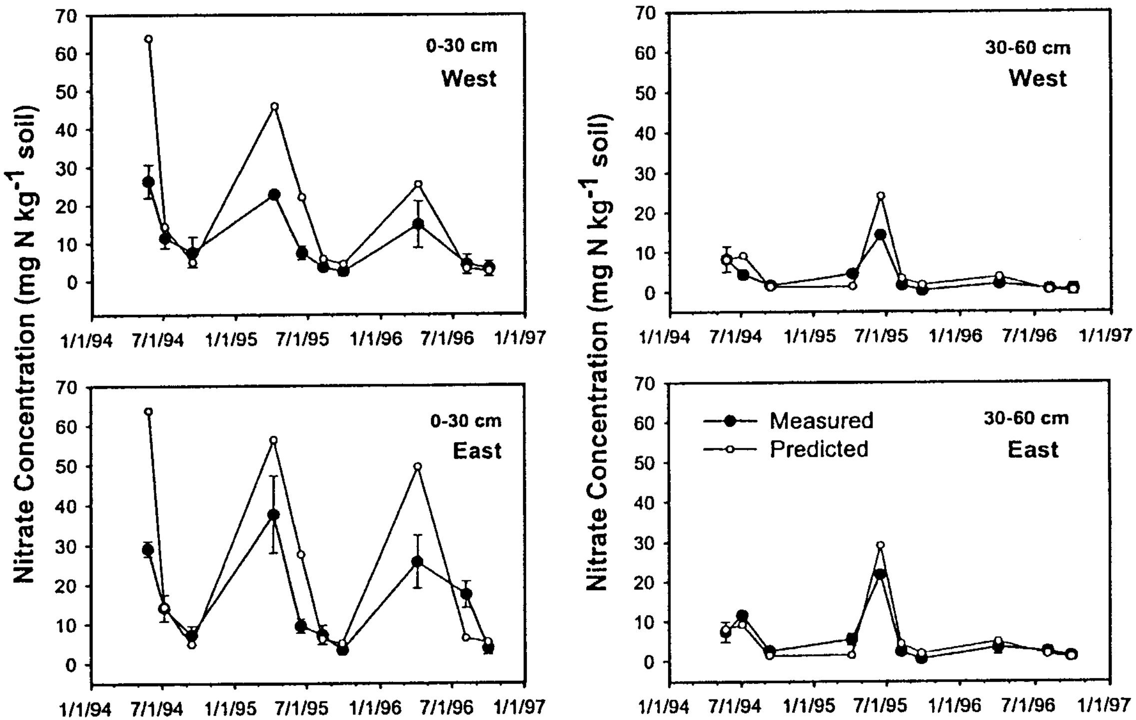


Figure 5 Measured and predicted NO_3 concentrations in the top 60 cm of the soil profile. East site received manure applications in Fall of 1993, 1994, and 1995; west site received manure application in Fall 1993 only (after Ma *et al.*, 1998a).

Table II

Irrigation Seasonal Amounts (in Centimeters) in the Akron, Colorado Study in 1984, 1985, and 1986[a]

			Irrigation amount (cm)			
Crop	Year	Irrigation method	1	2	3	4
Corn	1984	Solid set irrigation	2.30	6.81	10.62	N/T[b]
Corn	1985	Solid set irrigation	7.11	9.38	15.04	18.85
Corn	1986	Solid set irrigation	14.64	20.31	25.78	30.00
Soybean	1985	Solid set irrigation	0.28	3.38	8.86	12.92
Soybean	1986	Solid set irrigation	1.55	7.22	17.11	24.98
Soybean	1985	Rainout shelter irrigation	34.71	34.71	42.33	49.95
Soybean	1986	Rainout shelter irrigation	45.72	50.80	50.80	55.88
Soybean	1986	Drip irrigation	14.50	17.42	18.03	18.13

[a] Data from Ma *et al.* (2000a) and Nielsen *et al.* (2000).
[b] N/T, no treatment.

line-source irrigation system, with full irrigation next to the irrigation line and linearly declining water application as distance increased away from the line for all 3 years. Soybean experiments were conducted under the gradient line-source irrigation system in 1985 and 1986, a rainout shelter system in 1985 and 1986, and drip irrigation system in 1986. The model was calibrated for one irrigation level in 1985 and used to predict crop yield, biomass, height, and leaf-area index (LAI) for other irrigation treatments (Ma *et al.*, 2000a; Nielsen *et al.*, 2000).

For this study, the default soil hydraulic properties estimated from soil texture were used in RZWQM (Ahuja *et al.*, 1999b). Since no nitrogen stress symptoms were observed in the field, a no-nitrogen-stress mode was used in simulations to focus on water stress effects only. Both corn and soybean crop growth parameters were calibrated with data collected at irrigation level 1 in 1985 (Table II) and were tested at other irrigation levels and other years. To correctly simulate water stress effect on corn and soybean yields, a yield susceptibility curve was used to reflect water stress effect on photosynthesis at different growth stages (Sudar *et al.*, 1981; Ma *et al.*, 2000a; Nielsen *et al.*, 2000). Water stress also affects leaf-area index through CONVLA and the partitioning of carbohydrates between roots and shoots.

Table II shows the irrigation amounts in the 1984–1986 corn experiments (Ma *et al.*, 2000a). Generally, the model provided adequate predictions of corn growth and yield in all 3 years. As shown in Fig. 6, leaf expansion, plant height, and biomass were adequately predicted. Although model-predicted leaf senescence was delayed, predicted senescence rate was similar to experimental measurement. Corn yields were also within 1 standard derivation of the experimental values (Fig. 7). In addition, model predictions were better than or equal to (except for 1984

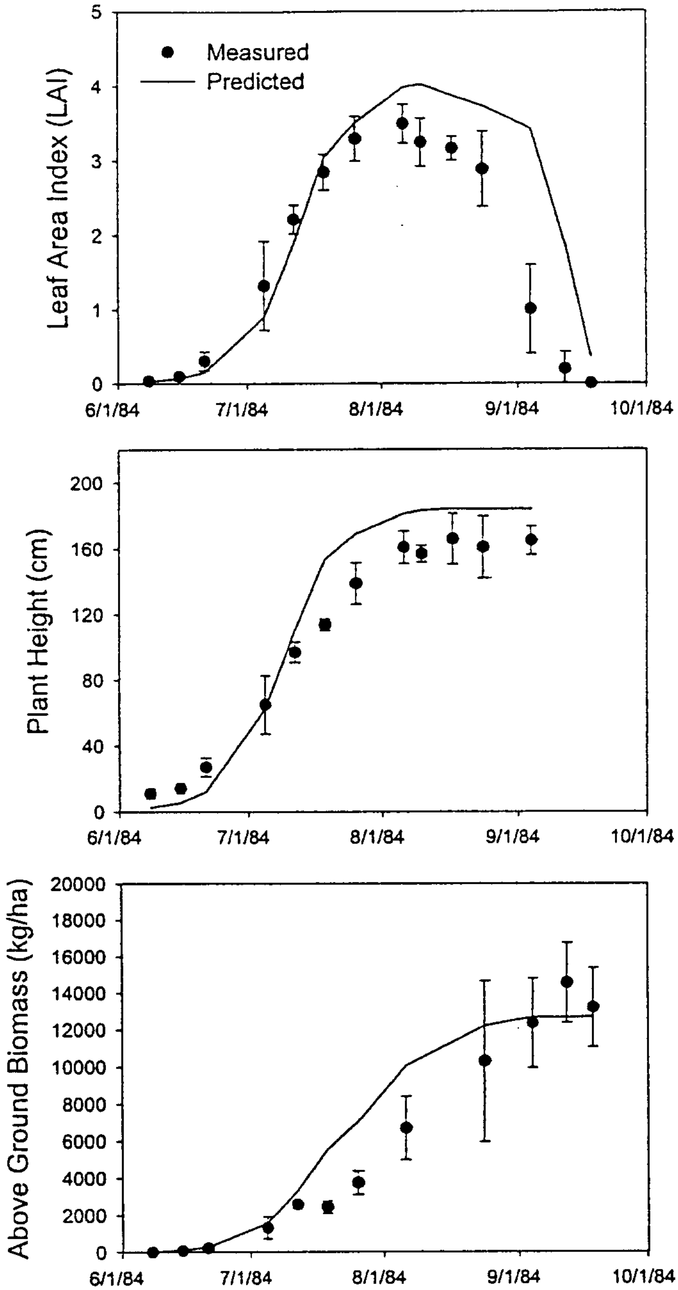


Figure 6 Measured and RZWQM predicted leaf-area index, plant height, and above-ground biomass during the growing season in 1984 at irrigation level 1, where 2.30 cm of water was irrigated between July 20 and September 2, 1984. Bars are 1 standard deviation around the mean (see Table I; after Ma *et al.*, 2000a).

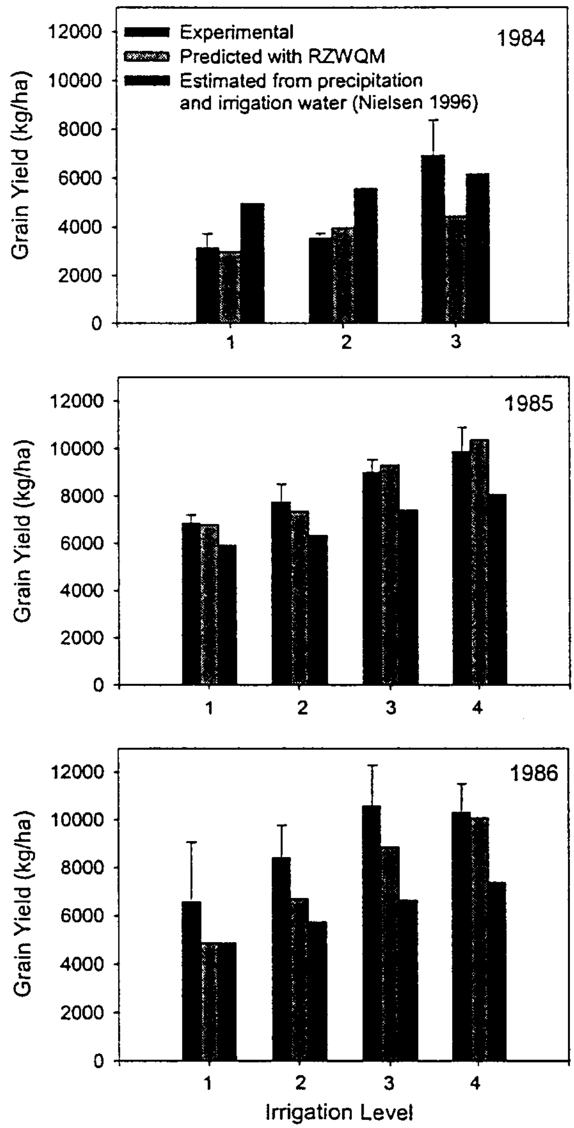


Figure 7 Measured and predicted grain yields in 1984 to 1986. Estimation from precipitation and irrigation water during July 15 to August 25 was based on Nielsen (1996). Bars are 1 standard deviation around the mean (after Ma *et al.*, 2000a).

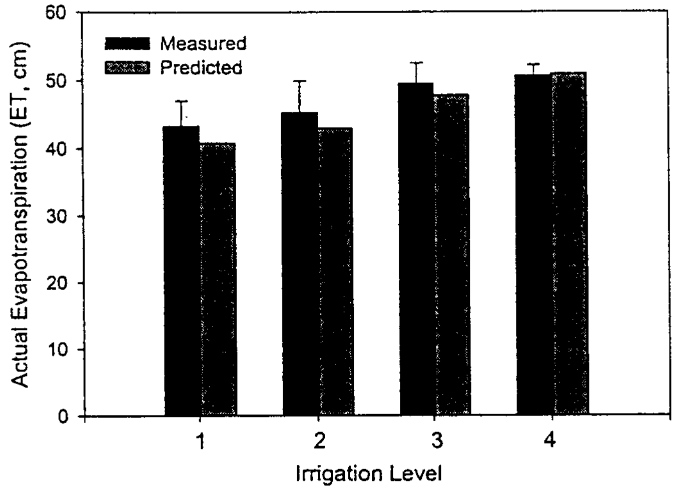


Figure 8 Estimated and predicted seasonal evapotranspiration in 1985 for all the four irrigation levels. Irrigation water was applied between June 29 and August 22, 1985, with 7.11 for level 1, 9.38 for level 2, 15.04 for level 3, and 18.85 for level 4. Bars are 1 standard deviation around the mean (see Table I; after Ma *et al.*, 2000a)

level 3 irrigation; Fig. 7) yields estimated from ET or available water (precipitation + irrigation water; Nielsen, 1996). The differences between model-predicted and measured ET were within 1 standard deviation of the experimental measurements (Fig. 8).

Four irrigation levels were implemented in the soybean study with total seasonal irrigation amounts shown in Table II. The model was calibrated for the 1985 solid set irrigation data set with the lowest amount of irrigation water and used for the 1985 and 1986 simulations, including simulations under rainout shelter and drip irrigation. Using soil hydraulic properties estimated from soil texture, the model provided adequate predictions of soil water contents and ET. Grain yield simulation was close to experimental values for all the irrigation levels under the solid set irrigation system (Fig. 9). Simulated LAI, biomass, and plant height were also in agreement with experimental values (Fig. 10). However, model-predicted plant height was much higher than measured values in 1986 for the solid set irrigation system. The year 1986 was a much drier year compared to 1985 and plant height response to water stress is not adequately represented in the model. RZWQM-predicted soybean yields under the rainout shelter study were comparable to experimental values but failed to respond to irrigation water levels (35 to 50 cm in 1985 and 46 to 56 cm in 1986) that are much higher than the amount applied by the solid set irrigation system (Table II).

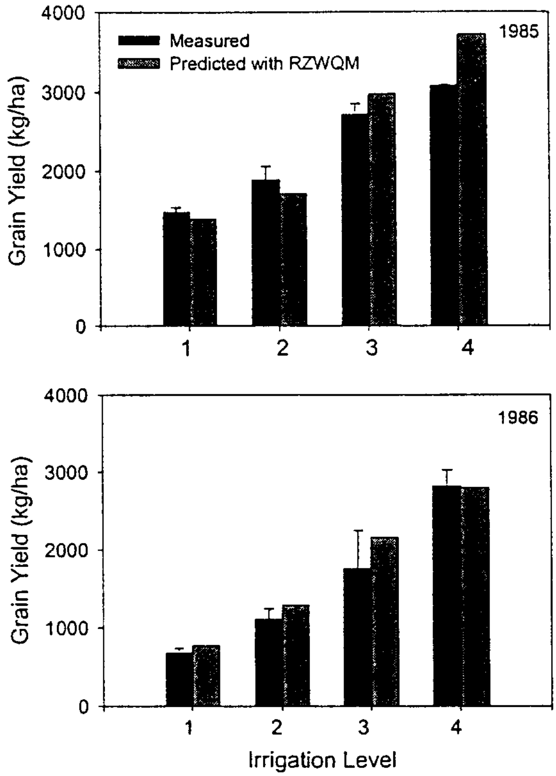


Figure 9 Measured and predicted soybean grain yield in 1985 and 1986 under solid set irrigation system at four irrigation levels (Table I; see Nielsen *et al.*, 2000 for detail).

The calibrated model for corn was further tested for corn yield responses to planting dates using the experimental data of Nielsen and Hinkle (1996). Two years of data were reported for 1991 and 1992 with planting dates of April 25, May 29, and June 18 of 1991; and April 30, May 19, and June 10 of 1992. The parameters calibrated for the 1984–1986 data (Ma *et al.*, 2000a) over predicted corn yields for the 1991 and 1992 data, possibly due to a deeper root system simulated by the model. If we limited rooting depth to 1 m, RZWQM simulated corn yields adequately (Fig. 11). The explanation may be that rooting depth was shallower in 1991 and 1992 compared to 1984–1986 because of irrigation during the vegetative stage in 1991 and 1992. As shown by Nielsen and Nelson (1998), water stress in early growing season promotes water uptake from deeper soil layers. Measured and simulated response of grain yield to planting dates is in agreement with the sensitivity analysis of the model (Ma *et al.*, 2000c).

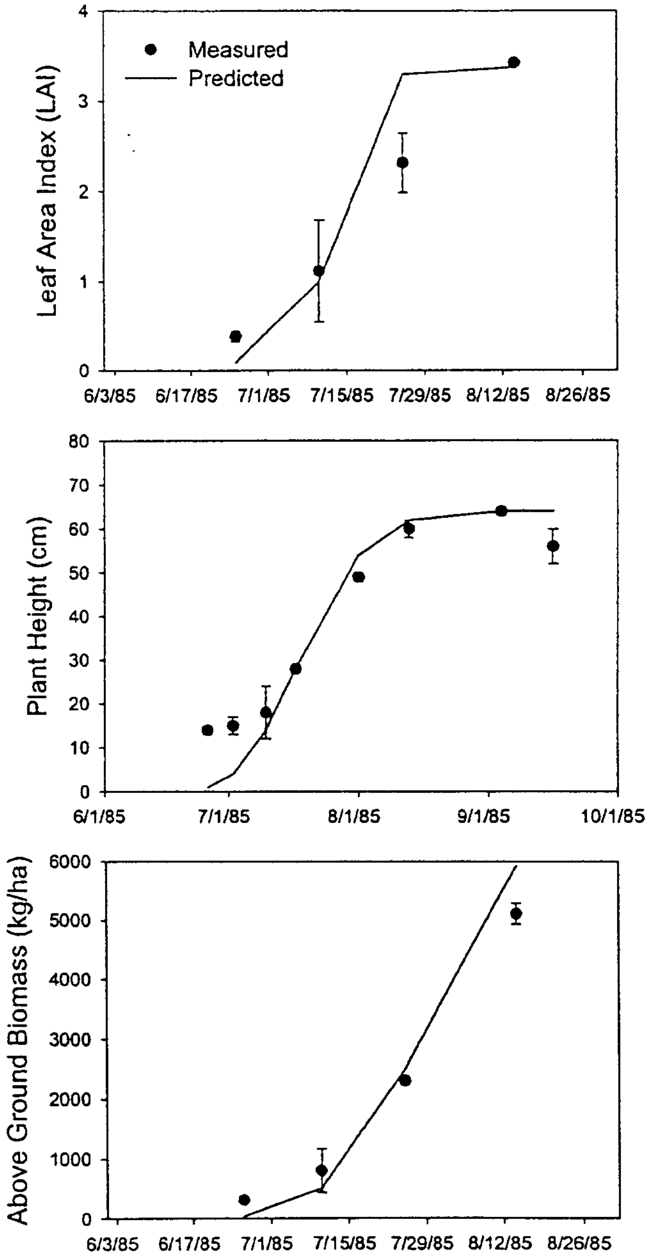


Figure 10 Measured and simulated leaf-area index (LAI), plant height, and above-ground biomass of soybean in a soybean study under solid set irrigation system at irrigation level 1 (see Table I; after Nielsen *et al.*, 2000).

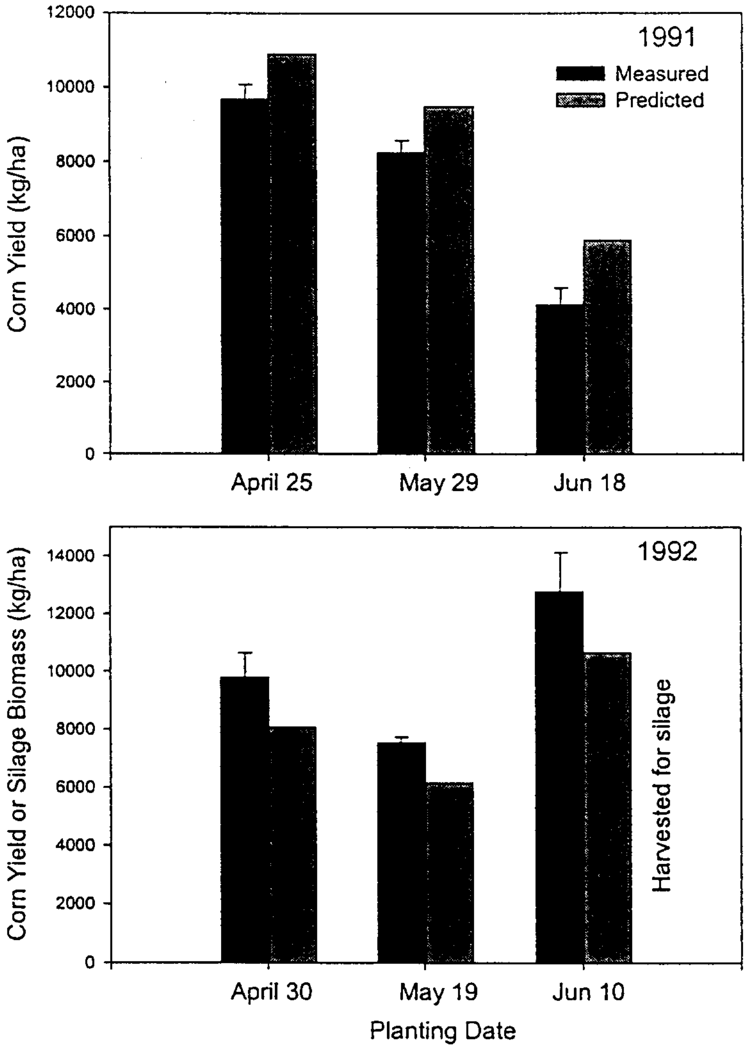


Figure 11 Measured and predicted corn yield as function of planting date. Corn planted on June 10, 1992 was harvested for silage. Bars are 1 standard deviation (see Nielsen and Hinkle, 1996 for details).

C. Colorado Study of Dry and Irrigated Corn

A dryland agroecosystem field study was established in 1985 to address water-use efficiency under various no-till crop rotation systems. Three sites were selected at Sterling, Stratton, and Walsh in eastern Colorado with observable soil topography of summit, side slope, and toe slope and soils ranging from loam to clay loam. Corresponding average daily air temperature was 9.8°, 10.4°, and 12.0°C and average yearly precipitation was 470, 430, and 440 mm (Ma *et al.*, 1999). Detailed experimental description and findings have been reported in numerous publications (Peterson *et al.*, 1999). RZWQM simulations were restricted to the wheat-corn-fallow system with focus on the 1991 corn phase only (Farahani *et al.*, 1999, 1995).

RZWQM was calibrated on data collected from the side slope in Sterling and used to predict experimental measurements from the rest of slopes in Sterling and all the slopes in Stratton (Farahani *et al.*, 1999, 1995). The Walsh site has not been simulated at this point. RZWQM correctly predicted higher LAI, yield, and water use in the toe slope than in the summit and side slopes at the Sterling site. However, due to estimation of no runoff from summit and side slope at Stratton onto the toe slope area, RZWQM significantly underpredicted soil water content after rainstorms in the toe slope, resulting in low yield and low LAI predictions for that slope. The lack of runoff in simulations was due to the use of daily rainfall, and thus a daily average rainfall intensity in the model. Actual rain intensity needed to be measured if runoff is important.

The center pivot irrigation study was based on data collected in 1972 and 1973 on a commercial farm near Crook, in the alluvial valley of the South Platte River in the northeastern corner of Colorado (Farahani *et al.*, 1999; Buchleiter *et al.*, 1995). The soil is a Julesburg loamy sand. Irrigation was limited to 20 to 25 mm per event. Data from 1972 were used to calibrate the model and data from 1973 were used for model evaluation. RZWQM performed better in simulating soil water movement than grain yield, biomass, and N uptake (Farahani *et al.*, 1999). Nitrate leaching was overpredicted by 79% primarily due to lower plant uptake and high soil N simulation. Again, recent improvements in simulating N dynamics and crop growth, along with improved estimation of soil hydraulic properties, should be tested on these data.

D. The Fayetteville, Arkansas Study of Manure Management

Field plots were established at the main Agricultural Experiment Station Farm, Fayetteville, Arkansas in the Fall of 1989 (Ma *et al.*, 1998b). The soil is classified within the Captina Series. The field had established tall fescue prior to experimental set-up. Saturated hydraulic conductivity of the soil was measured by the constant head method on undisturbed cores taken from just outside the site at various depths. Six plots were part of a randomized complete block design with three replicates. Half of the blocks were applied with broiler litters at 8.96 Mg/ha, whereas the rest were used as controls. Each plot had an area of 115.5 m^2 and was bordered by an earthen levee to control runoff and eliminate runon. Runoff was measured in a subarea of 11.55 m^2. Soil water pressure head, water content, and temperature were measured in each plot as a function of depth and time.

Soil hydraulic properties (Brooks–Corey parameters) were calculated from measured saturated hydraulic conductivity, 33-kPa soil water contents, soil texture, and soil water retention curve. Calibrated nutrient parameters from the Weld County, Colorado study (Ma *et al.*, 1998a) were used without modification. Measured biomass growth curves were used as substitute for plant growth. This study also assumed a fixed leaf area index and root distribution since the grass was well established before experiment was initiated. As opposed to the Weld County, Colorado study, this study assumed applied manure was available for microbial degradation immediately after application because of the more favorable soil condition under grass land than on bare soil surface (Ma *et al.*, 1998b).

As shown in Ma *et al.* (1998b), the model correctly simulated seasonal changes in soil water content (Fig. 12), soil water pressure head (Fig. 13), and soil temperature (Fig. 14). With nutrient parameters calibrated in a Colorado condition, the model provided soil nitrate responses to manure applications (Fig. 15). Simulated nitrate in runoff, N volatilization loss, and denitrification loss were within the experimental ranges reported in the literature. RZWQM estimated N mineralization rate was also close to values in the literature (Ma *et al.*, 1998b). However, the model overpredicted nitrate concentrations in soil solution at the 200-cm soil depth as compared with suction lysimeter samples. This discrepancy was attributed to preferential flow due to the fragipan at 80- to 114-cm soil depths, since cracks in the fragipan promote rapid loss of soil nitrate and prevent the suction lysimeter from obtaining representative soil water samples (Ma *et al.*, 1998b).

E. The MSEA–RZWQM Modeling Project

The Management Systems Evaluation Areas (MSEA) project was established in 1990 as a part of the Midwest Water Quality Initiative to evaluate the effect of agricultural management practices and systems on quality of water resources, to increase understanding of processes affecting water contamination, and to develop cost-effective strategies to reduce water contamination from pesticides and plant nutrients (Watts *et al.*, 1999). In 1991, the MSEA modeling group elected to evaluate RZWQM and the model was tested on the limited, commonly collected data. Therefore, the causes and effects could not be clearly discerned in many of the early RZWQM tests. Evaluation results of the RZWQM varied among the MSEA sites depending on the site-specific weather-soil-crop-management system. Soil water content was measured in all the MSEA sites and used to calibrate soil hydraulic properties. Soil N was measured and simulated in most of the MSEA sites. Pesticide was simulated in Minnesota, Missouri, and Iowa. Crop production

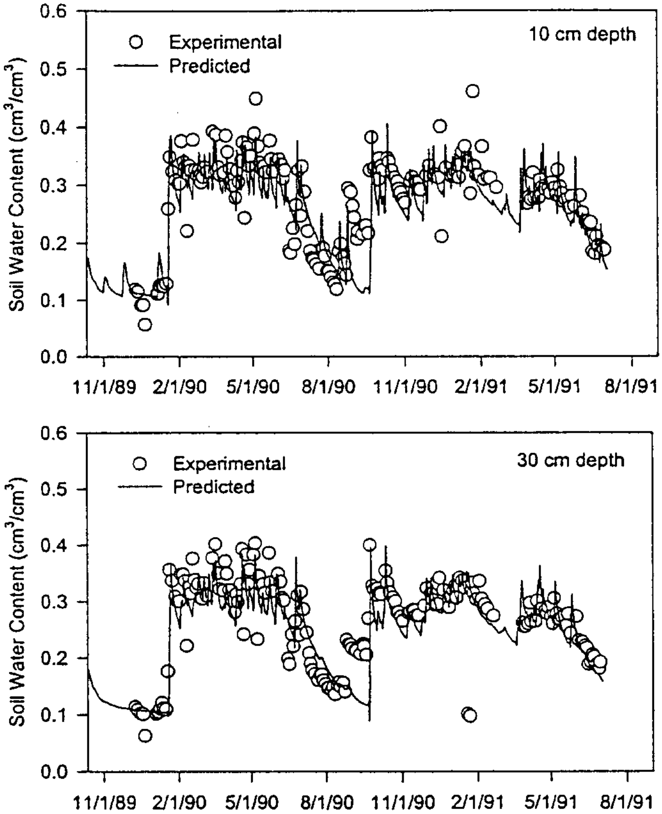


Figure 12 Measured and predicted soil water contents at soil depths of 10 (top) and 30 cm (bottom) in the control (no manure application) plots (after Ma *et al.*, 1998b).

was evaluated in Nebraska and Ohio. In spite of limitations noted above, the RZWQM–MSEA project was a good experience that benefited both the model and future experimentation greatly. Two more years (1995–1996) of data are available now upon the completion of the MSEA projects, and the MSEA data will be simulated with a now much improved version of the RZWQM.

1. The Minnesota MSEA

The Minnesota MSEA was located near Princeton, Minnesota in a region of outwash sands known as the Anoka Sand Plain. The soil is classified as Zimmerman fine sand (Wu *et al.*, 1999). A corn–soybean crop rotation was practiced with corn in 1992 and soybean in 1993. Management practices included ridge tillage with a

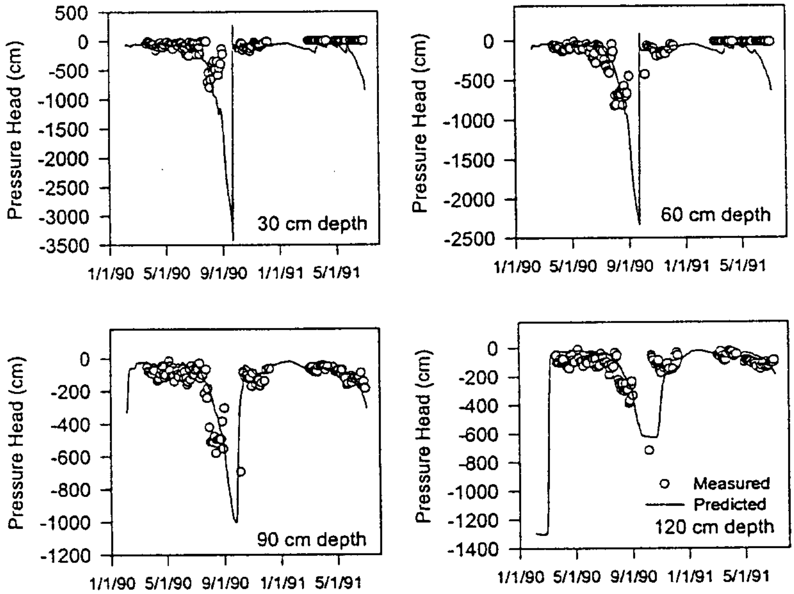


Figure 13 Measured and predicted soil water pressure head at soil depths of 30, 60, 90, and 120 cm in the control (no manure application) plots (after Ma *et al.*, 1998b).

banded application of alachlor and atrazine for corn and alachlor and metribuzin for soybeans. The soil water-retention curve and saturated hydraulic conductivity were measured with undisturbed soil cores in the laboratory, along with soil texture, organic carbon, and bulk density (Wu *et al.*, 1999). The experiment was designed to evaluate pesticide movement under a corn and soybean rotation.

As shown in Wu *et al.* (1999), the model was able to trace soil water dynamics well, especially in the top 35 cm of the soil profile. However, the model overpredicted soil water contents at lower soil depths using laboratory-derived Brooks–Corey parameters. Total water storage in the soil profile was thus overestimated. In a similar study with the same soil using the van Genuchten water-retention curve, Wu *et al.* (1996) found that soil hydraulic properties derived from field-measured water contents and hydraulic conductivity improved soil water prediction over the laboratory-derived parameters. Using an instantaneous pesticide adsorption model, the model reasonably predicted the peak position of pesticide concentrations in the top 15 cm of soil (Wu *et al.*, 1999). However, the tailing of pesticide dissipation curve was poorly predicted, which was attributed to pesticide adsorption–desorption kinetics that was not considered in the simulation. The RZWQM does allow for optional kinetics on adsorption sites in the soil, but unfortunately this option was not tested in the Minnesota MSEA, leaving kinetics as a speculation.

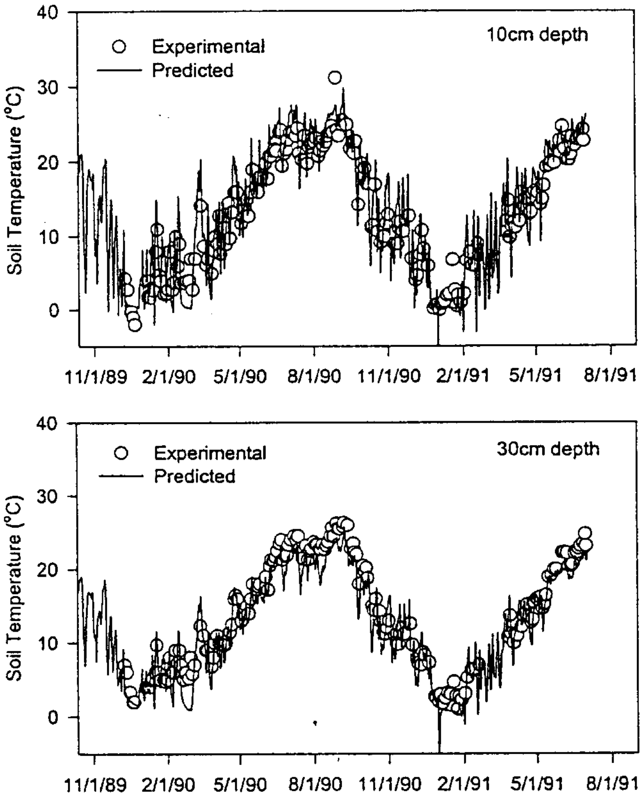


Figure 14 Measured and predicted soil temperature at soil depths of 10 (top) and 30 cm (bottom) in the control (no manure application) plots (after Ma *et al.*, 1998b).

2. Missouri MSEA

This study was on a claypan soil located in the Goodwater Creek Watershed. Two farming systems of corn–soybean rotations were evaluated with RZWQM with data collected from 1992 to 1994. The experimental measurements were above-ground biomass; crop yield; crop N uptake; and soil and solution concentrations of nitrate, atrazine, and alachlor (Ghidey *et al.*, 1999). Farming system 1 (FS1) was practiced with minimum tillage and Farming system 5 (FS5) was no-till. The surface-runoff component of RZWQM was evaluated with data collected from long-term runoff plots near Kingdom City, Missouri.

Measured soil bulk density, soil texture, and 33-kPa soil water content were used to estimate soil hydraulic properties. With model-estimated K_{sat} from effective porosity, surface runoff was underpredicted; therefore, K_{sat} was calibrated on

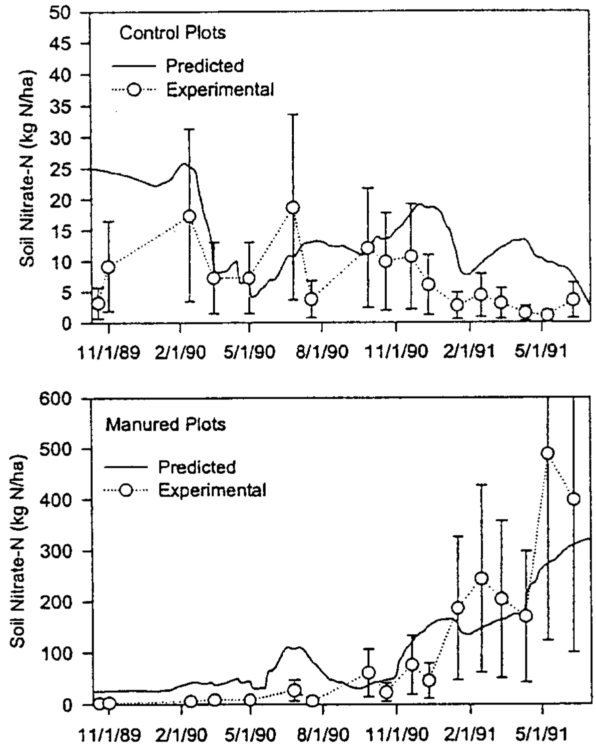


Figure 15 Measured and predicted soil nitrate-N in the top 90-cm soil profile in the control (top) and manured (bottom) plots from 1989 to 1991 (after Ma *et al.*, 1998b).

conventionally tilled corn plots at Kingdom City with consideration of surface crust. In addition, the model was also calibrated for macroporosity and degree of mixing (a parameter used to extract chemicals from surface soil) during rainfall events (Ghidey *et al.*, 1999). Corn growth was calibrated using 1992 FS1 data and soybean growth using 1992 FS5 data. Default parameters were used for N and pesticide processes. As shown in Table III, many of the attributes were well simulated except for soil nitrate (FS1) and soil alachlor (FS5) after harvest, but the author cautions that the observed data were limited. The model also correctly simulated total runoff amount, but there was variability between predicted and measured runoff for individual runoff events.

Predicted corn and soybean yields in 1993 and 1994 were within 15% of measured values except for those with extremely lower than normal yields due to disease, insect, or weed competition. Predicted NO_3-N, atrazine, and alachlor concentrations in the surface 0–5 cm were within 1 standard error (Ghidey *et al.*, 1999). However, similar to Wu *et al.* (1999) the model underpredicted alachlor persistence in the soil profile, indicating that the literature values of degradation

Table III

Comparison of Measured with RZWQM-Predicted Values after Calibration Using 1992 Minimum-Tillage (FS1) Corn and 1992 No-Till (FS5) Soybean[a]

Parameter	FS1 corn Measured	FS1 corn Predicted	FS1 corn % Difference	FS5 soybean Measured	FS5 soybean Predicted	FS5 soybean Difference
Aboveground biomass (kg ha^{-1})	14533	13088	−9.9	N/A[b]	7618	—
Grain yield (kg ha^{-1})	7219	7645	5.9	1969	1713	−13.0
N uptake by plants (kg ha^{-1})	153	152	<1.0	N/A	155	—
NO_3-N in soil profile before planting (kg ha^{-1})	46.7	44.8	−4.1	51.9	51.2	−1.4
NO_3-in soil profile after harvest (kg ha^{-1})	20.3	45.5	124.3	24.6	24.3	<1.0
Atrazine in soil profile before planting (g ha^{-1})	0.0	0.0	0.0	27.9	29.4	5.3
Atrazine in soil profile after harvest (g ha^{-1})	51.8	45.5	−12.2	12.5	8.3	−33.9
Alachlor in soil profile before planting (g ha^{-1})	0.0	0.0	0.0	8.1	7.9	−2.3
Alachlor in soil profile after harvest (g ha^{-1})	8.2	8.1	−1.2	5.2	13.9	169.4

[a]From Ghidey *et al.* (1999).
[b]N/A, not available.

constants may not apply here. Predicted NO_3-N concentrations in surface runoff were much higher than measured. On the other hand, atrazine and alachlor concentrations were considerably underpredicted for the first two runoff events after application (3 and 23 days), but were close to measured values for later events. The inability of RZWQM to account for variable soil cracking may be responsible for the simulation errors in chemical leaching, runoff loss, and soil moisture prediction within the claypan at soil depths of 38–58 cm. A water-content-dependent soil-cracking model has since shown promise in improving model simulations for the Missouri MSEA data set (Hua, 1995). Further model testing of the improved version should discern causes and effects in the above contradictory findings.

3. Iowa MSEA

The Iowa MSEA study was on a 9-ha subbasin within a 36-ha field near Ames, Iowa. The area is typical of subsurface drains with soils ranging from well-drained

Clarion loam to poorly drained Okoboji silty clay loam. The field had been in a long-term corn–soybean rotation with disk tillage in the fall after corn harvest (Jaynes and Miller, 1999). Corn was planted in 1992 and 1994 and soybean in 1991 and 1993. Soil moisture content was measured with a neutron probe and the soil water potential was monitored with tensiometers. Other experimental measurements included ET, crop yield, and nitrate and herbicide (atrazine and metribuzin) concentrations in the soil profile, drainage water, and surface runoff water (Jaynes and Miller, 1999).

The prevalent soil type, Clarion soil, in the subbasin was chosen for the RZWQM simulations. Soil hydraulic properties (e.g., the Brooks–Corey parameters) were obtained by fitting the model to measured soil water contents and potential heads. The model was calibrated for corn using the 1992 data and for soybeans using the 1991 data. Calibrated corn parameters underpredicted corn yield in 1994, which was drier than 1992. However, calibrated soybean parameters adequately predicted yield production in 1993 since both 1991 and 1993 were wet years. The results indicate that the simulation of water stress effect on crop growth and yield needs to be improved in the model and has been addressed by Ma *et al.* (2000a).

Soil water contents during growing seasons were adequately simulated in all the years. RZWQM-simulated ET was 5–25% lower than that calculated from Bowen ratio measurements in 1992–1994 (Fig. 16). The lower model prediction was later improved by limiting LAI effects on canopy resistance up to LAI values of 3 (Cameira, 1999). Although the model predicted the general trend of nitrate-N in the soil profile, nitrification of anhydrous NH_3 was predicted to occur much more quickly than was found in the soil, requiring changes in N dynamic parameters. The new improvements on these parameters made by Ma *et al.* (1998a,b) are expected to provide better simulation of N transformations in the soil. Pesticide residues were overpredicted for both atrazine and metribuzin when a lumped half-life was used for pesticide degradation. The use of two-stage degradation (half-lives of 5 and 40 days) improved atrazine prediction, but not metribuzin (Jaynes and Miller, 1999). Obviously, the pesticide degradation constants and sorption dynamics need to be measured on this site. Simulating macropore flow did not affect predicted yield, soil water content, and soil nitrate-N. Its improvement on the prediction of pesticide leaching varied from year to year (Jaynes and Miller, 1999).

4. Nebraska MSEA

The Nebraska MSEA was located in the North Platte River Valley near Shelton, Nebraska. The soil is Hord silt loam with continuous corn management. The MSEA site was established in 1991 and data from 1992 to 1994 were used for RZWQM evaluation (Martin and Watts, 1999). Five fertilizer treatments and three irrigation treatments were designed to evaluate the effect of management practices on corn yield, N uptake, plant biomass, LAI, and soil N. RZWQM was calibrated using 1992 experimental data from the middle-level irrigation and fertilizer treatments

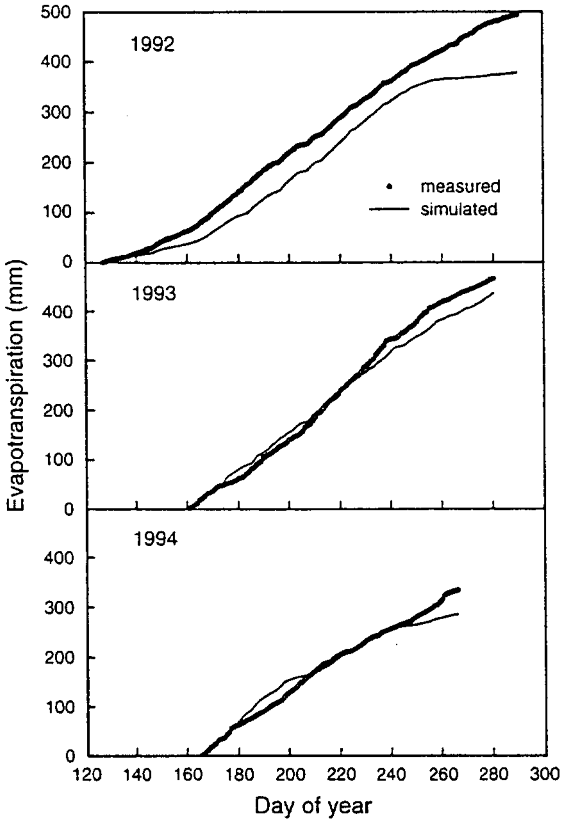


Figure 16 Measured and simulated cumulative evapotranspiration for 1992, 1993, and 1994 in the Iowa MSEA study (after Jaynes and Miller, 1999).

and then used to predict various model responses for the remaining treatments and years (1993 and 1994) (Martin and Watts, 1999).

The calibration of soil water content showed that laboratory-measured soil hydraulic properties were inadequate for simulating field data primarily due to spatial variability. Therefore, it was necessary to adjust some of the laboratory-derived parameters to predict field-observed soil water contents. The calibrated model provided better predictions of above-ground biomass and LAI than grain yield and N uptake (Martin and Watts, 1999). Simulated grain yield response to irrigation and fertilizer was poor in general, even in the 1992 calibration year. On one hand, the insensitivity of grain yield to management practices warrants further study of the plant growth modeling approaches used in RZWQM. The improvement of modeling water stress response simulation by Ma *et al.* (2000a) should help better simulate the Nebraska MSEA data. On the other hand, measured yield variability could be attributed to wind damage (e.g., in 1994) that is not considered in the model. Simulated plant N uptake and total soil inorganic N were not adequate, and the data should be reevaluated with the new soil N transformation parameters reported by Ma *et al.* (1998a,b).

5. Ohio MSEA

The Ohio MSEA was located in Pike County, Ohio on a Huntington silt loam soil. The model was evaluated for both continuous corn (Nokes *et al.*, 1996) and a corn–soybean rotation (Landa *et al.*, 1999) with emphasis on crop production (yield and biomass), soil water content, and soil nitrate-N. Although pesticides (atrazine, alachlor, and metribuzin) were measured in soil samples, they were not simulated with RZWQM. For both crop management systems, the 1992 data were used for RZWQM calibration and 1991 and 1993 data were used for validation. The Ohio MSEA collaborators used the GLEAMS N database to estimate the fast, medium, and slow organic pools (Nokes *et al.*, 1996; Landa *et al.*, 1999) rather than running the model for a number of years to initialize the pools.

In the continuous corn rotation study of Nokes *et al.* (1995, 1996), calibrated soil water contents were higher than measurements in August to November, 1992, which was explained by the low ET prediction due to low leaf biomass simulation. Since the authors were unable to derive a set of model parameters that would allow adequate predictions of all plant attributes (leaf biomass, stem biomass, and grain yield), they gave grain yield the priority at the expense of leaf and stem biomass prediction. As a result, the calibrated model provided good predictions for grain yield in all 3 years (Nokes *et al.* 1996). Since plant growth depends primarily on water and N, good stem and leaf biomass predictions were obtained in 1993 when soil water and N concentrations were adequately predicted.

In the corn rotation study, soil water contents were adequately predicted except during the late growing season in the corn rotation phase (Landa *et al.*, 1999). Surface soil N concentrations were overpredicted for the corn and underpredicted for the soybean phase. Predictions of leaf and stem biomass and seed biomass were reasonable given the large variation in field measurements. Final grain yields were better predicted for corn than for soybean (Landa *et al.*, 1999). Further studies should focus on more critical evaluations of why contradictory simulation results were obtained for different crops.

F. Nashua, Iowa Study of Tile-Drained Agricultural Systems

A series of studies have been conducted since 1977 in Nashua, Iowa to evaluate effects of tillage and other management practices on water quality and crop yield in tile-drained soils. Tile drains were installed about 1.2 m deep at 28.5-m spacing in 1979 (Azevedo *et al.*, 1997b). The study site is located on loam soils. Long-term tillage treatments included no-till, chisel plow, moldboard plow, and ridge till. The site has also been used recently to study swine manure (Kumar *et al.*, 1998a; Bakhsh *et al.*, 1999). The RZWQM was used to simulate tile flow (Singh and Kanwar, 1995a; Singh *et al.*, 1996), nitrate-N in tile flow (Singh and Kanwar, 1995b; Kumar *et al.*, 1998a, 1999; Bakhsh *et al.*, 1999), and atrazine in soil and tile drainage (Azevedo *et al.*, 1997a; Kumar *et al.*, 1998b).

Calibration and evaluation of the tile drain component of RZWQM have been the major focus of the Nashua, Iowa study. The criterion for model calibration was to minimize the difference between the measured and predicted cumulative tile flow for the growing season, with due consideration to time of peak flow by calibrating initial soil water contents (not measured) (Singh and Kanwar, 1995a; Singh *et al.*, 1996). In the study of Singh and Kanwar (1995a) on a Kenyon loam soil, RZWQM was calibrated using 1990 data for each type of tillage practice and then evaluated using 1991 and 1992 data. As shown in Table IV, RZWQM predicted total tile flow reasonably well. Although the model underpredicted peak flow for large rainfall events (wet year) and overpredicted peak flow for small rainfall events (dry year),

Table IV

Total Seasonal Predicted and Observed Tile Flows for 1990–1992[a]

		Subsurface drain flow (mm)[b]			
Year	Total rain (mm)	CP	MB	NT	RT
1990	939				
(DOY 100–300)	Observed*	183	90	275	191
		(52.6)	(28.9)	(7.8)	(61.2)
	Predicted	197	107	290	221
	Percentage difference	7.6	18.9	5.4	15.7
1991	592				
(DOY 70–200)	Observed*	264	174	312	315
		(46.6)	(28.8)	(26.4)	(41.5)
	Predicted	309	184	315	310
	Percentage difference	17	5.4	1	1.5
1992	732				
(DOY 70–250)	Observed*	80	64	92	70
		(15.4)	(32.0)	(46.2)	(5.4)
	Predicted	88	78	109	96
	Percentage difference	10	21.8	18.5	37.1

[a] Singh and Kanwar (1995a).

[b] CP, chisel plow; MB, moldboard plow; NT, no-till; RT, ridge-till.

*Average of three replications. Values in parentheses are standard deviation.

time of peak flow was well predicted. In addition, the model successfully predicted the trend of tillage effects on tile flow; that is, maximum flow occurring under no-till and minimum flow under moldboard plow in 1990 and 1991. No significant difference in flows among tillage practices was predicted in 1992. Macropore flow and rainfall intensity were critical to successfully predict peak flow under no-till conditions (Singh and Kanwar, 1995a). These simulation results were later extended to all three soils (Kenyon, Readlyn, and Floyd) in Nashua, Iowa (Singh *et al.*, 1996).

Singh and Kanwar (1995b) further simulated nitrate-N losses to tile flow based on a calibrated tile flow component (Singh and Kanwar, 1995a). The model was initialized at the beginning of tile flow each year (1990–1992) to match nitrate-N concentrations in the first tile drainage sample by adjusting initial soil nitrate-N concentrations (not measured) in the soil profile. The initialized model was then used to predict nitrate-N in subsequent drainage events of that year. Table V shows nitrate-N losses under different tillage systems from 1990 to 1992. Generally the model adequately simulated tillage effects on NO_3-N losses, given the experimental errors observed. Simulated tillage effects were even more consistent with observed trends in terms of average NO_3-N concentration in tile flow (Singh and Kanwar,

Table V

Total Seasonal Predicted and Observed Nitrate Losses in Tile Flows for 1990–1992[a]

		NO_3-N losses with subsurface drain (kg/ha)			
Year	Total rain (mm)	CP	MB	NT	RT
1990	939				
	Observed*	100.0	58.0	107.2	87.4
		(30.7)	(20.8)	(21.6)	(24.6)
	Predicted	94.5	70.7	95.1	81.3
	Percentage difference	5.5	21.8	11.3	7.0
1991	592				
	Observed*	75.4	61.8	60.4	57.4
		(10.4)	(8.7)	(2.4)	(12.7)
	Predicted	83.0	60.3	60.1	65.1
	Percentage difference	10.0	2.4	0.5	13.4
1992	738				
	Observed*	12.6	12.3	10.9	7.9
		(1.3)	(10.7)	(7.8)	(2.1)
	Predicted	10.3	14.9	12.8	10.5
	Percentage difference	18.3	21.1	17.4	32.9

[a] Singh and Kanwar (1995b).
[b] CP, chisel plow; MB, moldboard plow; NT, no-till; RT, ridge-till.
* Average of three replications. Values in parentheses are standard deviation.

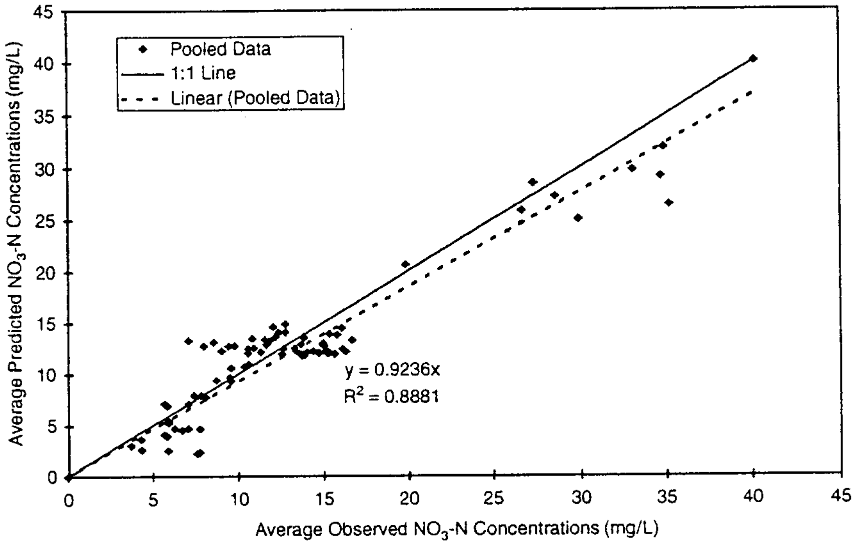
1995b). Nitrate-N distribution in the soil profile was generally poorly predicted; however, this may be due to inadequate simulations of water movement, inaccurate predictions of N uptake, and insufficient calibration of carbon/nitrogen dynamics (Kumar *et al.*, 1999).

The RZWQM was also used to study the effect of swine manure application on water quality in Nashua, Iowa (Kumar *et al.*, 1998a; Bakhsh *et al.*, 1999). Manure was applied in the Fall of each year from 1992 to 1995 and data were collected in 1993–1996. Kumar *et al.* (1998a) reported part of the study on the Kenyon loam soil from 1993 to 1995 with continuous corn rotation and Bakhsh *et al.* (1999) published additional data on the Kenyon and Readlyn loam soils from 1993 to 1996 with a corn–soybean rotation. Kumar *et al.* (1998a) calibrated RZWQM using 1993 data and used 1995 data for model evaluation. Data from 1994 were not used because it was a dry year with only a few drainage events. As shown in Fig. 17, RZWQM adequately simulated nitrate-N in subsurface drainage and in the soil profile. Bakhsh *et al.*, (1999) obtained similar results with the corn–soybean rotation fields, where the model was calibrated using 1993 (corn) and 1994 (soybean) data and evaluated using the 1995 (corn) and 1996 (soybean) data.

On the same experimental site, the pesticide atrazine was also simulated with RZWQM (Azevedo *et al.*, 1997a; Kumar *et al.*, 1998b). Azevedo *et al.* (1997a) reported the simulation results of atrazine concentrations in the soil profile under moldboard plow and no-till for 1990–1992. Atrazine half-life and adsorption constant (K_{oc}) were calibrated using 1990 data and validated using 1991 and 1992 data. Simulation results were evaluated for maximum error and coefficient of determination (r^2). Azevedo *et al.* (1997a) found that RZWQM correctly simulated the depth of atrazine penetration and range of atrazine concentration. The experimental study was further examined by Kumar *et al.* (1998b) for atrazine losses to tile drains. The RZWQM was capable of predicting atrazine concentrations and total losses in tile drains when macropore flow was included in simulations (Kumar *et al.*, 1998b). They also found that timing of peak discharge of atrazine was adequately predicted. Simulation results also showed that macropore flow had no effect on drainage flow but significantly improved atrazine transport predictions. Although atrazine concentration in the soil profile was not reported in Kumar *et al.* (1998b), increased leaching of atrazine through macropore should decrease simulated atrazine concentration in the soil profile and therefore improve atrazine predictions in the soil (Azevedo *et al.*, 1997a).

G. The Portugal Study of Mediterranean Crop Systems

A comprehensive study was carried out in Portugal from 1996 to 1998 in two typical Mediterranean cropping systems to evaluate alternative irrigation and fertilizer management practices. The two soils were a poorly drained silt loam soil



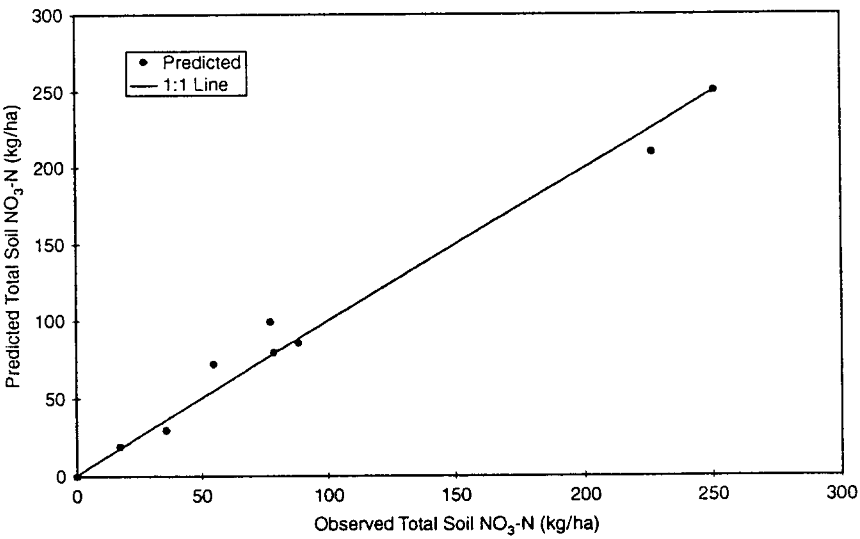


Figure 17 Measured vs predicted NO_3-N concentrations in subsurface drain water (top) and total NO_3-N in the top 120 cm soil profile for 1993 and 1995 in the Nashua, Iowa study (after Kumar *et al.*, 1998a).

and a sandy soil with very rapid drainage. There was a shallow water table in the silt loam soil with the water table located between 50 and 150 cm deep during crop season. Soil hydraulic properties were determined in laboratory soil cores as well as from field measurements. A tension infiltrometer was used to quantify macroporosity (Cameira, 1999). Nitrate and ammonium were measured in the soil systems. Data on LAI, plant height, rooting depth, plant biomass, and N uptake were also collected.

RZWQM was calibrated on the silt loam soil using the 1996 data and on the sandy soil using 1997 data. Calibrated parameters were then validated with 1998 data on both soils (Cameira, 1999). Based on the study of Cameira *et al.* (2000), macropore flow was modeled in the silt loam soil to correctly simulate infiltration rate and soil water contents. Generally, RZWQM provided reasonable simulations of LAI, plant height, rooting depth, biomass, ET, soil moisture, soil water pressure, water uptake, water seepage, nitrate distribution in the soil profile, and N uptake in all the years (Cameira, 1999). Examples of simulated results are shown in Fig. 18. Model validation for these variables was also considered good for 1998. Therefore, in spite of soil differences between the two cropping systems, RZWQM adequately simulated crop production once calibrated for that system.

H. Other Miscellaneous Field Studies

A variety of other studies combining field measurements with RZWQM simulations have been reported in the literature. Ahuja *et al.* (1996) investigated pesticide and bromide behavior in a loamy sand soil in The Netherlands. The field was installed with a drainage system at a 0.9-m soil depth. The concentrations of chemicals cyanazine, metribuzin, and bromide were measured periodically after application. RZWQM predictions of soil water and bromide distributions were adequate for most of the sampling days. Assuming a two-site sorption mechanism along with first-order degradation of pesticides in soil solution, RZWQM accurately simulated pesticide concentration in the soil profile for all sampling dates with $r^2 > 0.83$ (Fig. 19).

In a North Carolina study, Johnsen *et al.* (1995) tested the drainage component of RZWQM for three drain spacings (7.5, 15, and 30 m) at a 0.9-m depth and obtained fairly good predictions of water-table fluctuations. However, they found that RZWQM slightly overpredicted water-table depth. In a Portugal study, Cameira *et al.* (1998) evaluated RZWQM for water and nitrate movement under three different N fertilizer treatments (single broadcast of urea, single fertigation of UAN, and multiple fertigation of UAN). Simulated total water storage in the soil profile, total soil nitrate, corn yield, and seasonal water and nitrate transport were within 5% of measured values (Cameira *et al.*, 1998). As shown in Fig. 20, the model correctly responded to fertilizer management as well. However, the model

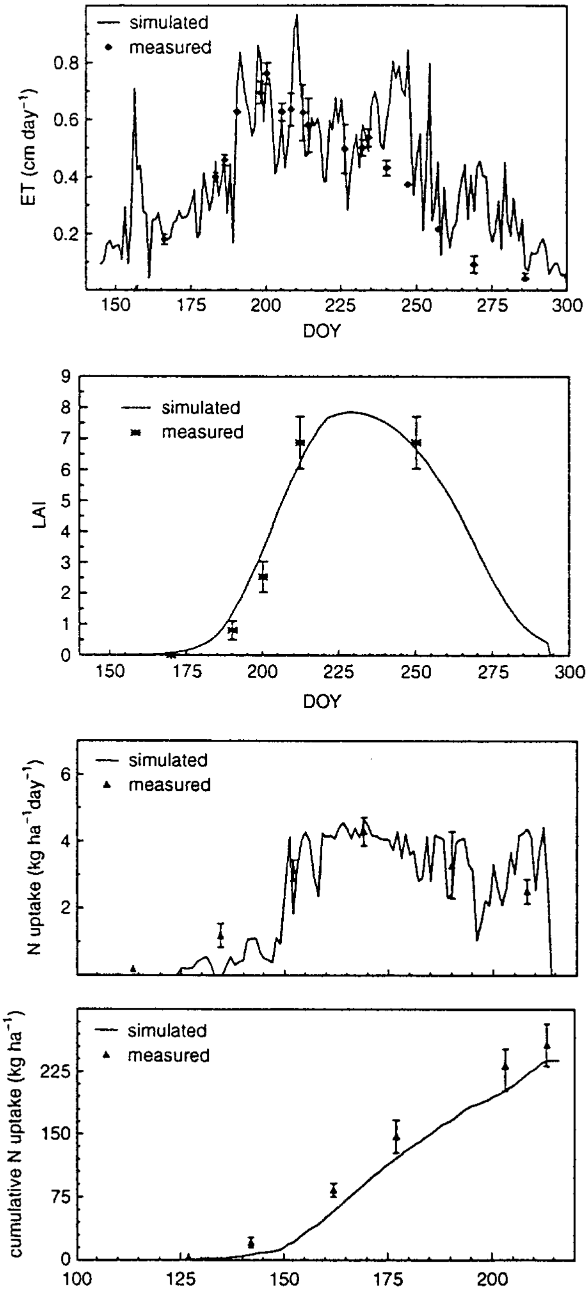


Figure 18 Measured and simulated evapotranspiration, leaf-area index (LAI) for the silt loam soil in 1996 (top two plots), and daily and cumulative plant N uptake rate for the sandy soil in 1997 (bottom two plots) in a Portugal study (after Cameira, 1999).

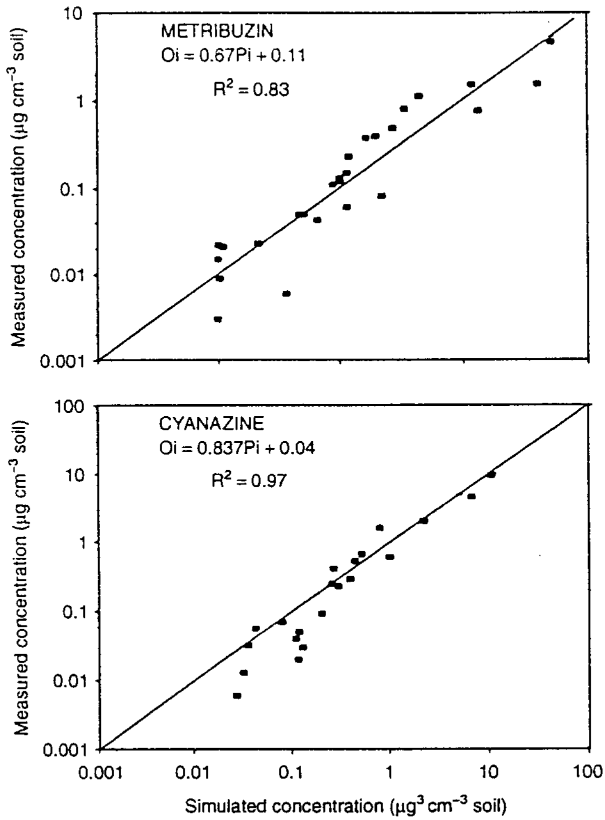


Figure 19 Measured vs predicted cyanazine and metribuzin in the soil profile in a field test of RZWQM for the Dutch data (after Ahuja *et al.*, 1996).

overpredicted water and nitrate movement because of a high K_{sat} value used for the compacted surface layer.

Ma *et al.* (1995) simulated atrazine transport in the soil profile and runoff water using experimental data from Watkinsville, Georgia. They assumed a single equilibrium sorption site coupled with a two-stage degradation of atrazine in soils; that is, a fast degradation process between application and first rainfall and a slow process thereafter. They found that RZWQM adequately simulated atrazine distribution in the soil profile and atrazine losses to runoff (Ma *et al.*, 1995). Inadequately simulated atrazine distributions for two sampling dates were attributed to experimental errors and/or limitations of the instantaneous equilibrium adsorption assumption. In a later study at Tifton, GA, on a loamy sand soil, Ma *et al.* (1998d) found that RZWQM underpredicted ET and runoff, but overpredicted

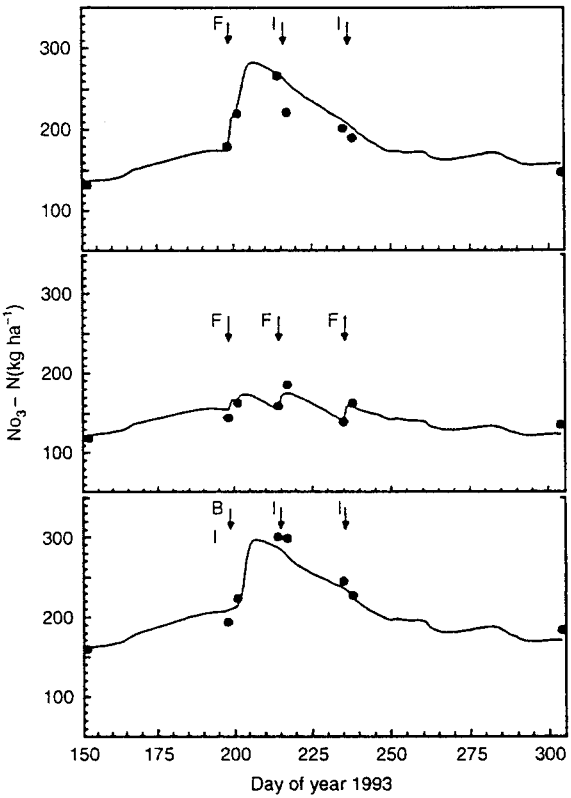


Figure 20 Total soil profile (120 cm) nitrate-N contents during the 1993 growing season for treatments of single and multiple fertigation of UAN and surface broadcast applications of urea I: irrigation, F: fertigation, B: broadcast application. (after Cameira *et al.*, 1998).

percolation with laboratory-measured soil hydraulic conductivity. A sensitivity analysis showed that runoff was highly sensitive to K_{sat}, soil porosity, and surface crusts/seals (Ma *et al.*, 1998d). Simulated runoff was not significantly different from measured values when K_{sat} was decreased by 15% based on experimental error in K_{sat} measurement, when surface crusts/seals were considered, or when wheel tracks were simulated.

Borah and Kalita (1998) compared RZWQM- and LEACHM- (Leaching Estimation And Chemistry Model) simulated nitrate and atrazine transport on two Kansas soils (clay and sandy soils). Water samples were taken periodically with suction lysimeters at different soil depths and analyzed for nitrate-N and atrazine concentrations. Both models correctly simulated the trend of measured concentrations. However, RZWQM performed better than LEACHM and MLEACHM

(LEACHM with macropore component) on predicting atrazine concentrations in 1995 and 1996 on sandy soil. Results also showed that the macropore flow component in RZWQM improved nitrate and atrazine predictions in the clay soil.

VI. MODEL APPLICATIONS IN LABORATORY STUDIES

RZWQM has also been applied to laboratory column studies for evaluation of selected soil processes. Ahuja *et al.* (1995) tested the macropore flow component of RZWQM for bromide (Br) and water movement in 16 soil columns with treatments of macropore vs no macropore, surface aggregates vs no surface aggregates, and air-dry vs saturated initial soil water content. The soil was a Kirkland silty clay loam. The model adequately simulated both water and Br distribution in the soil columns without macropore and surface aggregates 30 min after infiltration. However, peak Br concentration in the soil columns with surface aggregates, but without macropore, was underestimated (Fig. 21). Simulations of water and Br

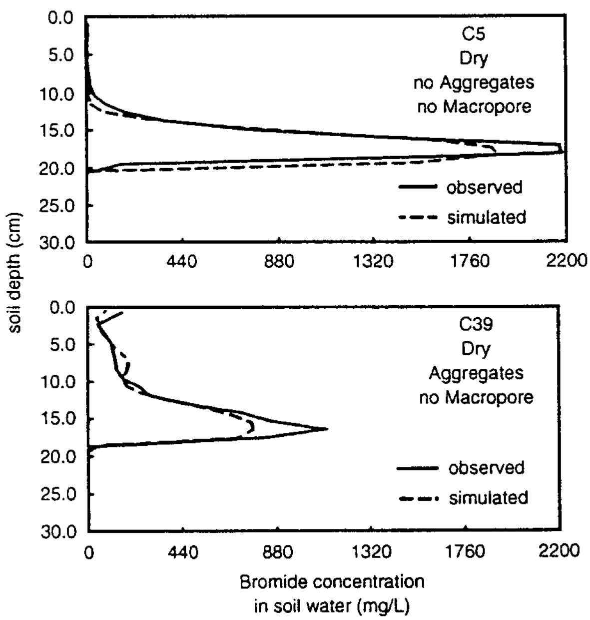


Figure 21 Comparison of observed and simulated soil Br concentration distributions for initially dry columns without macropores, with and without surface aggregates (after Ahuja *et al.*, 1995).

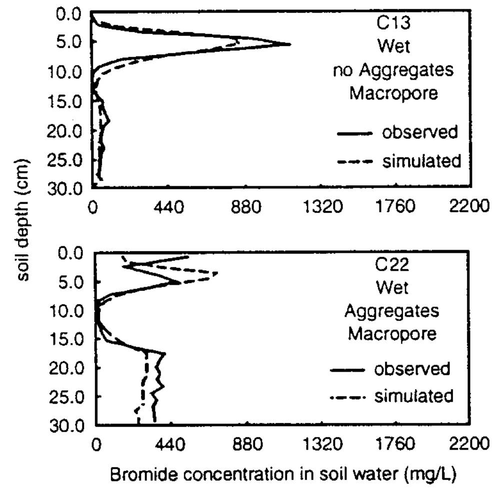


Figure 22 Comparison of observed and simulated soil Br concentration distributions for initially wet columns with macropores, with and without surface aggregates (after Ahuja *et al.*, 1995).

in columns with macropore and without aggregates were generally good for both initially wet and dry soil columns. Again, Br distribution in columns with surface aggregates (with macropore) was not predicted as well as in columns without surface aggregates (Fig. 22). Therefore, the effects of surface aggregates on the partitioning and transport of surface-applied chemicals need to be further improved (Ahuja *et al.*, 1995).

Malone *et al.* (2000) applied the RZWQM to the macropore flow study using undisturbed soil blocks obtained from a no-till cornfield (30 × 30 × 30 cm). The soil blocks were maintained at three initial moisture levels (0.11, 0.17, and 0.21 kg water/kg soil) 1 h before simulated rain (30 cm in 0.5 h). Percolation was collected at the base of the soil block using a 64-cell grid lysimeter (Shipitalo and Edwards, 1996). Area occupied by macropores with diameters >2 mm was approximately 0.5% at the base of the soil block. Malone *et al.* (2000) showed that RZWQM did not predict percolate volume and percolation timing when a macroporosity of 0.5% was used. The reason was that not all the macropores were effective in conducting water (or contributed to flow). Therefore, they used an effective macroporosity concept in their model simulation. Figure 23 shows calibrated cumulative water percolate volume at the three initial soil-moisture levels. Calibrated effective macroporosity was 0.05, 0.075, and 0.1% for the dry, intermediate, and wet initial conditions, respectively. Such a trend in effective macroporosity was supported by Shipitalo and Edwards (1996), who found that the number of cells contributing to flow was much less under dry conditions than under wet conditions, although

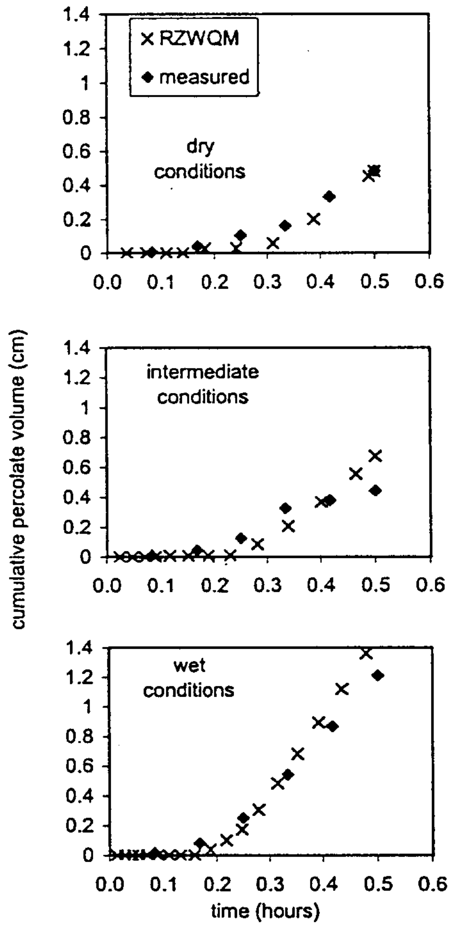


Figure 23 Measured and RZWQM-simulated cummulative water percolate volume. An effective macroporosity of 0.05, 0.075, and 0.1% were used for dry, intermediate, and wet initial water content, respectively. The total measured visible macroporosity (diameter > 2 mm) was about 0.5% (after Malone *et al.*, 2000).

contribution from an individual cell was much greater under dry conditions than under wet conditions. Another reason for using effective macroporosity was that the macroporosity estimated by Shipitalo and Edwards (1996) was for one cross section at the base of the block only, and no macroporosity was measured at the soil surface which is very important for generating macropore flow. The third reason was that RZWQM used a single, constant macroporosity without considering possible change in macropore size with soil moisture content. The work of Hua

(1995) on variable cracking will be incorporated into the model and it should improve simulation of macropore flow. Since macropore flow occurs unevenly among macropores, more work is needed on the macropore flow mechanism due to microtopography and water repellency (Ritsema and Dekker, 1995).

In another study using packed soil boxes of a Tifton loam sand, Ma *et al.* (1996) tested the RZWQM for pesticide transport. The soil boxes were equipped with leachate- and runoff-sampling devices. Atrazine, fenamiphos, and Br were applied to the soil boxes and their concentrations in leachate and runoff were analyzed under simulated rainfall. The model simulated Br and water leaching well; however, pesticides were not simulated well when an instantaneous adsorption assumption was used. Both atrazine and fenamiphos were adequately simulated when a two-site equilibrium-kinetic adsorption mechanism was invoked (Ma *et al.,* 1996).

Cook (1996) applied RZWQM to study tillage effects on water movement in soil columns containing Minnesota silt loam and found that macropore water transport was required to obtain correct partitioning of water into leachate and runoff. The author further noticed that the fraction of deadend macropores (not continuous macropores) was very sensitive in calibrating water partitioning and was able to reproduce water distributions in soil cores from three tillage systems (12-yr no-till, 2-yr no-till, and 12-yr moldboard plow) by calibrating saturated hydraulic conductivity and the fraction of deadend macropores. However, calibrating the model for water flow did not satisfactorily simulate chemical transport. On the contrary, measured hydraulic conductivity and matric flow without macropores provided the best predictions of chemical transport when instantaneous equilibrium sorption was assumed. Predicted atrazine distributions in the soil profile were close to experimental measurements in the topsoil layer, but were progressively underpredicted at lower depths. Kinetics of pesticide sorption should have been investigated in this study.

VII. FUTURE DEVELOPMENT

Since RZWQM requires representative values for model parameters that often vary across the field because of spatial variability (Martin and Watts, 1999), model parameters should best be treated as a distribution rather than as a single value (Ma *et al.,* 1998b). In addition, since some of the input parameters are correlated, future efforts should investigate the relationship between those parameters (Buchleiter *et al.,* 1995). The inconsistency of the role of macropores in chemical transport and surface runoff warrants further study on soil macroporosity, such as introducing the variable cracking (Ghidey *et al.,* 1999, Jaynes and Miller, 1999; Hua, 1995) or effective macroporosity (Malone *et al.,* 2000). So far the model only simulates N dynamics; phosphorus soil dynamics is needed, especially for manure management applications. Movement of mobile organic matter in the soil profile is needed for long-term simulations. Further studies on plant responses to water and nitrogen stresses and on parameterization of new crops (e.g., wheat) are also imminent focuses of the RZWQM development team. Although RZWQM documentation has provided some guidelines on how to apply the model, the calibration and evaluation procedure varies with data availability and model objectives (Ma *et al.*, 1998a,b). More work is needed in standardizing model calibration and database development (Hanson *et al.*, 1999).

All components of RZWQM have not been equally evaluated due to lack of experimental data. Ideally, RZWQM should be evaluated for all the components using the data set from a single experiment. In reality, no such a data set exists for RZWQM evaluation. The most common research situations include only part of the information required. This leaves a great deal of freedom for model parameterization, resulting in model parameters that are seldom transferable to other experimental conditions. As an agricultural system model, further work is needed in evaluating the responses of RZWQM to various agricultural management practices, such as irrigation, fertilization, manure application, and pesticide management at multiple locations (Ma *et al.*, 2000c). In addition, several new components of the model have been developed for RZWQM, but they await further evaluation before incorporation into the released version. Examples of these components are the daily soil and residue temperature prediction module (Aiken *et al.*, 1997), the soil heat transport module for soil freezing and snowpack (Flerchinger *et al.*, 1999, 2000), the overland-flow and sediment-routing module (Bierbaum *et al.*, 1999), and the gas emission module (Xu *et al.*, 1998).

With confidence developed through numerous applications, interest has been shown in linking RZWQM to a geographic information system (GIS) and using RZWQM as a foundation for a decision support system (DSS) with economic analysis capability. Development of a DSS has gained support from the USDA-ARS and it will be implemented after further testing with recently updated MSEA data. Part of the significance of RZWQM–DSS is that RZWQM has been shown to successfully simulate management effects and thus it is ready for use in technology transfer (Ma *et al.*, 2000c). The DSS project will include further quantitative evaluation of all the management practices against experimental data. Finally, since there are several ways to simulate an agricultural process, effort has been made to modularize RZWQM so that users can test different model assumptions and select appropriate modules for their specific purposes.

VIII. SUMMARY AND CONCLUSION

As shown in Table VI, RZWQM has been tested for different aspects of water movement (ET, soil water content, runoff, tile drain, and water-table fluctuation), several pesticides (atrazine, alachlor, metribuzin, prometryn, fenamiphos,

Table VI

Studies Combing Field Research with RZWQM Simulations[a]

Authors	Exp. site/year	Soil/Crop	Management practices: Tillage	Fertilizer	Irrigation	Pesticide	Exp. measurements
Ahuja *et al.* (1996)	The Netherlands, 1981–1982	Loamy sand	Cultivator harrow	N/A	N/A	Cyanazine metribuzin	Soil water content, Br and pesticides distributions
Bakhsh *et al.* (1999)	Iowa, 1993–1996	Loam/corn, soybean	Chisel plow	Swine manure	N/A	N/A	Tile flow, nitrate in tile flow
Borah and Kalita (1998)	Kansas, 1995–1997	Silty clay loam, sandy loam/corn	N/A	UAN	N/A	Atrazine	Nitrate and atrazine in soil water samples (suction lysimeters)
Cameira *et al.* (1998)	Portugal, 1993	Silty loam/corn	Disk harrow rotary tiller	Urea, UAN	Flood	N/A	Soil water content, water table, soil nitrate-N
Cameira (1999)	Portugal, 1996–1998	Sand, silty loam/corn	N/A	Urea, UAN	Flood, sprinkler	N/A	Soil water content, soil water pressure, water uptake, ET, LAI, yield, biomass, soil N, N uptake N leaching, plant height, rooting depth
Ellerbroek *et al.* (1998)	Colorado, 1991–1992	Loamy sand	N/A	N/A	Sprinkler	Metoachlor	Metolachlor in ground water and soil samples, hydraulic conductivity, dye tracer
Farahani *et al.* (1999)	Colorado, 1991	Clay loam, loam/corn	No-till	UAN	N/A	N/A	Soil water content, yield
Farahani *et al.* (1999)	Colorado, 1972–1973	loamy sand/corn	Disking, chisel plow, cultivator	NH_4NO_3 anhydrous NH_3	Sprinkler	N/A	Soil water content, soil nitrate yield, biomass, N uptake
Ghidey *et al.*, (1999)	Missouri, 1992–1994	Silt loam/corn, soybean	Field cultivator, no-till	UAN	N/A	Atrazine, alachlor	Soil water content, above-ground biomass, yield, N uptake, soil nitrate, atrazine and alachlor concentrations in soil profile and runoff

Ghidey *et al.* (1999)	Missouri, 1983, 1985 1990, 1993	Silt loam/corn, soybean fallow	Moldboard plow disking, field cultivator, no-till	NH_4, NO_3	N/A	N/A	Surface runoff
Jaynes and Miller (1999)	Iowa, 1992–1994	Loam/corn, soybean	Disking, no-till	MAP, anhydrous NH_3	N/A	Atrazine, metribuzin	Soil water content, nitrate-N and pesticide concentrations in soils and deep seepage (drainage), ET
Johnsen *et al.* (1995)	North Carolina, 1974–1976	Sandy loam/ corn, soybean, potato, wheat	N/A	N/A	N/A	N/A	Water table fluctuation
Kumar *et al.* (1998b)	Iowa, 1990–1992	Loam/corn	Moldboard plow no-till	N/A	N/A	Atrazine	Subsurface drainage flow, atrazine in drainage, macroporosity
Landa *et al.* (1999)	Ohio, 1991–1993	Silt loam/corn, soybean	Chisel plow, disking	Liquid 28, anhydrous NH_3	N/A	Atrazine, alachlor metribuzin	Soil water content, soil nitrate and above-ground biomass, and grain yield
Ma *et al.* (1995)	Georgia, 1973–1975	Sandy loam/corn	N/A	N/A	N/A	Atrazine	Runoff, atrazine in runoff, soil water content, atrazine in soil profile
Ma *et al.* (1998a)	Colorado, 1993–1996	Sandy loam/ silage corn	Moldboard plow field cultivator	Beef manure	Alternative furrow, flood	N/A	Soil water content, soil N, N uptake, silage yield
Ma *et al.* (1998b)	Arkansas, 1990–1991	Silt loam/tall fescue	No-till	broiler litter	None		Soil water content, soil water pressure head, soil N, N uptake, soil temperature, biomass, runoff, N in runoff and suction lysimeter waters.
Ma *et al.* (1998d)	Georgia, 1992–1993	Loamy sand/ corn	Disk harrow, Moldboard plow, rototill,	UAN	Sprinkler	N/A	Surface runoff

continues

Table VI—*Continued*

Authors	Exp. site/year	Soil/Crop	Management practices: Tillage	Fertilizer	Irrigation	Pesticide	Exp. measurements
Ma *et al.* (2000a)	Colorado, 1984–1986	Silt loam/corn	Disking	NH_4NO_3	Sprinkler	N/A	Soil water content, plant biomass, yield, plant height, LAI, ET
Martin and Watts, (1999)	Nebraska, 1992–1994	Silt loam/corn	Disking	NH_4NO_3	Sprinkler	Atrazine, metolachlor	Soil water content, nitrate and ammonium-N in soil, LAI, biomass, N uptake, yield.
Nielsen *et al.* (2000)	Colorado, 1984–1986	Silt loam/ soybean	Disking	N/A	Sprinkler, flood, drip	N/A	Soil water content, plant height, biomass, yield, LAI, ET.
Singh and Kanwar (1995b)	Iowa, 1990–1992	Loam/corn	Moldboard plow, chisel plow, no-till, ridge-till	N/A	N/A	N/A	Tile drainage flow, nitrate in tile flow and soil profile
Walker (1996)	Illinois, 1992–1993	Silty clay loam/corn, soybean	Conventional till reduced till, no-till	N/A	N/A	N/A	Tile flow, nitrate in tile flow
Wu *et al.* (1999)	Minnesota, 1992–1993	Sand/corn, soybean	Ridge tillage	N/A	N/A	Atrazine, alachlor, metribuzin	Soil water content, pesticide concentration in soil sample

[a] UAN, urea-ammonium-nitrate; N/A, not available; LAI, leaf-area index; ET, evapotranspiration; MAP, monoammonium phosphate.

metolachlor, and cyanazine), crop growth (corn and soybean), nitrogen dynamics, and several agricultural management practices (manure management, irrigation, tillage, fertilization, and crop rotation). The model has been used nationally and internationally with data collected from 1972 to 1996 (Table VI). The degree of success in RZWQM application depended on the agricultural system simulated, data availability and quality, processes of interest, and, to some extent, the modeling experience of users. Both the successes and failures of the model have provided information to improve the model and data collection. During these numerous calibration and validation exercises, many new ideas have been developed on model application (Hanson *et al.*, 1999; Ma *et al.*, 1998a). RZWQM applications have furthered understanding of agricultural systems and promoted the integration of models with field research.

Many important component issues have been addressed in the context of a system approach using RZWQM, such as the macropore flow, water table fluctuation, tile drains, fertilizer applications, surface crop residue management, manure applications, pesticide fates, tillage effects, and water management. In agricultural systems, water balance is the key because of its role as a mediator in plant growth and chemical transport. Any simulation error in water prediction will be propagated and reflected in the simulation of other components of the system, such as plant water uptake, plant responses to water stress, and nitrogen availability. The organic matter/nitrogen cycling component also determines nitrogen availability and affects plant growth and nitrate leaching. Unfortunately, there are no measurement methods for soil organic and microbial pools available to tie down this component. Therefore, Ma *et al.* (1998a) suggest running the model for 10 or more years to stabilize these pools. Simulated plant growth depends not only on photosynthesis and carbon/nitrogen partitioning, but also on nutrient and water availability determined by other RZWQM modules. Agricultural management is the driving force in the model and has effects on all simulated processes. All these components and their interactions need to be more extensively tested and improved.

For a given experimental data set, there are a number of ways to calibrate RZWQM depending on data availability, calibration criteria, simulation error tolerance, and the interest and experience of model users, since an agricultural system is usually represented by many model parameters. Therefore, calibrated model parameters and interpretation of results may be different by different model users for a given data set. In addition, due to the large degrees of freedom in model calibration, there may be more than one set of model parameters that give nearly the same simulation results. Model users usually select a set of model parameters that satisfy all the experimental conditions. Although most model users claim that they use one set of data for calibration and the other set for validation, in most cases, they select the one that gives the smallest simulation errors for all the data sets. This is a very common practice in applying agricultural system models and is called the "prediction-correction" method. Furthermore, model users may adjust some related model parameters manually without relying on an optimization scheme. This trial-and-error experience or "prediction-correction" method requires some educational training and can be frustrating for new (as well as experienced) model users.

In most RZWQM applications, the model is calibrated using 1 year of experimental results and then evaluated with data from other years. This type of evaluation procedure may not be effective if weather conditions are similar in all the study years. Another technique is to calibrate the model in one location and evaluate in another location as done by Farahani *et al.* (1999) and Ma *et al.* (1998a,b). This strategy is appropriate only when evaluating a particular management effect. A better way is to calibrate RZWQM under one management practice and evaluate under others as done by Ma *et al.* (2000a) and Martin and Watts (1999). Ideally, model evaluation should cover a broad range of management effects and locations. Also, one should keep in mind that there are many agronomic factors not simulated in RZWQM, such as diseases and disasters. Model users need to know the limitation of the models and make interpretation accordingly.

Generally, good model prediction depends on model (input) parameters and model concepts as well as on representative experimental data. Some of the model parameters are experimentally measured at one spot, with no respect to considerable variability in the field, such as for soil type, saturated hydraulic conductivity, depth of each horizon, and macroporosity. Evaluation of a model can only be objective if model users can provide representative model input parameters. There are also considerable errors in experimental measurements under field conditions, such as soil water content, tile drainage nitrate and pesticide concentrations, and crop yield. In addition, data collection may not be balanced or complete. Furthermore, some model parameters cannot be measured in one single experiment, therefore, users have to resort to other sources for model input parameters, e.g., estimation from literature or initialization of the model itself or calibration of certain parameters to achieve desired output. Improved model parameterization and prediction will only be achieved if experimentalists and model developers work together on collecting the right type of data and their variability in the field and in testing and evaluation of the concepts in the model. In the long term, integration of modeling and field research will help both parties and make the process of generating new knowledge and technology more focused and efficient.

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