

Modeling the effects of agricultural management practices on groundwater in Shelton, USA

Modelación de los efectos de prácticas de manejo agrícola en el agua subterránea en Shelton, EELILI

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An integrated methodology was developed to assess the impact of recharge rates, nitrate leaching from crop root zones, and irrigation pumping rates on groundwater quality and quantity. Monthly values for deep percolation of water, irrigation pumping and leaching of nitrate-nitrogen were calculated with a soilwater-plant model. An Intermediate Vadose Zone Model (IVZM) was developed and used together with models for groundwater flow (MODFLOW) and solute transport (MT3D) to simulate the movement of water and nitrate-nitrogen. The IVZM generates recharge files used by MODFLOW and MT3D. The methodology was applied to an area near the town of Shelton, Nebraska, where a shallow sand-gravel aquifer is highly contaminated by nitrate-nitrogen. MODFLOW was calibrated using historic groundwater level data from 1981 to 1996. Simulation results suggest that concentration reductions of 10% in the upper third of the saturated zone are possible after 10 years of improved irrigation and nitrogen fertilizer management. Groundwater quality changes slowly propagate down-gradient from the field and towards the lower part of the aguifer. A particle tracking technique showed that water from a well does not provide a good indication of the influence of improved management in the adjacent field. The quality of water pumped from a well represents the effect of management over 15 years and from more than 1.5 km up-gradient from the well. Regional groundwater quality depends on local management practices over a long period. Regulatory programs to improve water quality require therefore, widespread adoption and substantial time to provide significant water quality improvements.

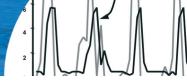
Keywords: groundwater, modeling, recharge, water quality, agricultural management practices

Se desarrolló una metodología integrada para evaluar el impacto en la calidad y cantidad de agua subterránea ocasionado por la tasa de recarga, infiltración de nitrato desde zonas de cultivos, e intensidad de bombeo para irrigación. Se calculan valores mensuales de percolación profunda, irrigación por bombeo e infiltración de nitrato-nitrógeno con un modelo de suelo-agua-planta. Un modelo de zona vadosa intermedia (IVZM) fue desarrollado y usado junto con modelos de flujo de agua subterránea (MODFLOW) y transporte de soluto (MT3D) para simular el movimiento del agua y nitrato-nitrógeno. IVZM genera archivos de recarga usados por MODFLOW y MT3D. La metodología fue aplicada a un área próxima a la localidad de Shelton, Nebraska, donde un acuífero somero de arena y grava está altamente contaminado por nitrato-nitrógeno. MODFLOW fue calibrado usando registros históricos de nivel de agua de 1981 a 1996. Resultados de simulaciones sugieren que reducciones de un 10% de la concentración en el tercio superior de la zona saturada son posibles después de 10 años de mejoras en el manejo de riego y de fertilizantes de nitrógeno. Los cambios en la calidad del agua subterránea se propagan lentamente gradiente abajo desde el terreno cultivado hacia la parte inferior del acuífero. Una técnica de rastreo de partículas mostró que el agua de pozo no entrega una buena indicación de la influencia de la mejora en el manejo en terrenos adyacentes. La calidad del agua bombeada de un pozo representa el efecto del manejo sobre 15 años y de más de 1.5 km gradiente arriba del pozo. La calidad del agua subterránea regional depende de prácticas locales de manejo sobre un periodo largo. Programas de regulación para mejorar la calidad del agua requieren por lo tanto ser adoptados ampliamente y con tiempo suficiente para lograr mejoras significativas de la calidad del agua.

Palabras clave: agua subterránea, modelación, recarga, calidad del agua, prácticas de manejo agrícola

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Introduction

The Central Platte Valley of Nebraska, shown in Figure 1, is an area of intensive agricultural production where nitrate pollution of groundwater has increased since it was first detected in 1961. Currently about 200,000 ha are underlain by groundwater with a nitrate-nitrogen NO-N concentration in excess of the 10 mgl⁻¹ maximum contaminant level established for drinking water. The vast majority of municipalities and rural dwellings in the region use groundwater for potable water. To curtail the buildup of NO-N, the Central Platte Natural Resources District (CPNRD) implemented a groundwater management program in 1987. The goal was to encourage farmers to apply the necessary amount of nitrogen (N) fertilizer by taking into account the mineral N available from the soil and irrigation water, thereby increasing the fraction of N fertilizer used by the crop and reducing nitrate leaching (CPNRD, 1996). In 1990, the Nebraska Management Systems Evaluation Area (MSEA) project was established in the Central Platte Valley to develop practical and economical practices to improve groundwater quality (Figure 1). The project established a field research site near the town of Shelton.

The effects of agricultural practices on groundwater quality are difficult and expensive to measure. Modeling provides an alternate to estimate the effects of improved practices on groundwater quality; however, accurately estimating recharge, pumping and pollutant loading of the aquifer are essential (Oyarzún et al., 2007). The effect of the vadose zone on recharge and pollutant loading of groundwater has not been widely considered (Canter, 1997). Most groundwater modeling studies use the amount of recharge as a calibration parameter and neglect how changes in agricultural practices or land use affect recharge. They often ignore the buffering effect of the vadose zone on the movement of water and solutes. Additionally, complex models that simulate water and solute transport in the vadose zone are usually not linked to groundwater models because such models are often too large and complex for regional-scale modeling (Gusman and Mariño, 1999).

The objective of this work was the development of an integrated groundwater model for the area surrounding

the Nebraska MSEA site for the estimation of NO₃-N concentrations in an aquifer. This results from the use of alternative practices for irrigation and N management, tillage and other production practices. The size of the modeled area was determined by the location of physical features that provide stable boundary conditions, the location of the MSEA site and the direction of the groundwater flow, which is generally parallel to the Platte River, with a slight northerly component leaving the river. Regionally, this tendency did not change materially between 1930 and 1990 (Kilpatrick, 1996). In addition, the uncertainty about the east and west boundary conditions made it useful to have a buffer zone between these boundaries and the study site.

The integrated model has four main components. The soil-water-plant model simulates crop production to estimate crop yield, nitrate leaching, irrigation pumping and deep percolation from crop root zones. The intermediate vadose zone model (IVZM) simulates the effect of the intermediate vadose zone on water and solute recharge to the groundwater system. A groundwater flow model is used to calculate the dynamic behavior of the groundwater system and a solute transport model is used to simulate changes in groundwater quality.

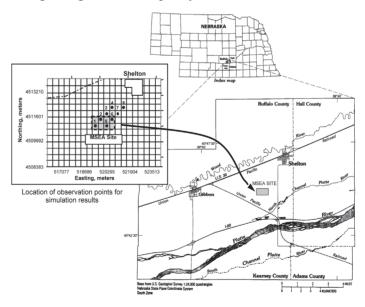
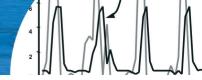


Figure 1: Location of the study area and the Nebraska MSEA site (adapted from Kilpatrick, 1996). The observation points for tracking simulated groundwater quality changes are shown in the insert.



Integrated model Hydrogeological model

A groundwater model was developed to simulate the behavior of the aquifer beneath the MSEA project site (Arumi, 2000). The groundwater system beneath the site consists of two aquifers: an upper alluvial aquifer and a confined aquifer that is a part of the Ogallala formation. The hydraulic connection between the two aquifers is not significant (Peckenpaugh and Dugan, 1983; Diffendal and Smith, 1996). Irrigation and fertilization practices have strongly impacted the quality and quantity of groundwater in the upper aquifer. In contrast, the Ogallala is little used for irrigation in this region and has low levels of nitratenitrogen. For that reason, this study focuses on the upper aquifer.

The computer code MODIME was used for management of groundwater simulations (Zhang *et al.*, 1996). This code corresponds to a pre-processor and post-processor for MODFLOW, PATH3D and MT3D that makes the linkage between these models and uses the same interface to process simulations. An important feature of MODIME is its capability to interpolate data from the regional groundwater model to create a sub-model. The code uses input and output from a larger model to interpolate the results in a smaller area inside the original model. This allows the simulation of local conditions using finer details while retaining regional boundary conditions. The sub-model area was large enough so that boundary conditions did not affect simulation results near the MSEA site.

Data needed for the model consisted of geological and hydrological information such as the watershed configuration and hydraulic characteristics from geologic test-hole logs. Data about soils, cropping patterns, irrigation and well location were also compiled. Historical groundwater data were used for calibration and verification (Kilpatrick, 1996; McGuire and Kilpatrick, 1998). The main sources of information were the University of Nebraska's Conservation and Survey Division, the U. S. Geological Survey, the Central Platte Natural Resources District and the Nebraska Department of Natural Resources.

A series of recharge and pumping events is necessary to produce long-term simulations. An extended time series of deep percolation and pumping was generated with the EPIC model (Sharpley and Williams, 1990; Williams *et al.*, 1990) to provide stress on the groundwater system. The percolation series represents the monthly volume of water that drained from the root zone. The pumping series represents the volume of water applied for irrigation including losses resulting from inefficient application. The percolation and pumping series were developed for each soil association in the area.

With the exception of local variations produced during the irrigation season or temporal variations produced in extremely wet years, such as 1993, the regional water table configuration is quite stable. Kilpatrick (1996) and McGuire and Kilpatrick (1998) compared the regional water table configuration between 1931 and 1991. They found a constant shape for the water table. During calibration of the groundwater model it was observed that very strong variations of recharge (or discharge) were necessary to produce a significant alteration of the water table configuration. This is because of the strong effect of the Platte River on the groundwater system and the high transmissivity of the upper aquifer. The model is not very sensitive to aquifer hydraulic conductivity or storage coefficient values. Simulations using hydraulic conductivities of 50 and 150 m/day produced nearly identical results. The lack of sensitivity probably explains the different values of hydraulic conductivity determined for the area by McGuire and Kilpatrick (1998) and Peckenpaugh and Dugan (1983).

Soil-water-plant model

The effect of agricultural practices on the water and nitrate balance in the root-zone was simulated using the EPIC model. The model simulates crop systems and biophysical processes in the root zone. Bredeweg (1994) calibrated EPIC to simulate irrigation and fertilization practices at the Nebraska MSEA site, using weather data from Grand Island, Nebraska. Yildirim *et al.* (1997) simulated best management practices for corn irrigated by a center pivot in the area and found EPIC to be reliable for calculating the volume of water that percolates from the root zone.

For modeling purposes, homogeneous management units based on soil, crops and irrigation practices were defined.

The geographic distribution of the soil associations was obtained from the Nebraska Department of Natural Resources database for Hall and Buffalo Counties (Table 1). There are three principal zones: upland, valley and floodplain. The upland area is dominated by the Coly soil associations, the valley by Hord, Wood River, Blendon and Gibbon associations, and the floodplain by the Platte River soil association. The most intensively irrigated agricultural production is located in the valley. In the upland and the floodplain the predominant use is pasture and range land. A summary of the cropping patterns according to zone, soil and irrigation method is summarized in Table 2. Each combination of soil, crop and irrigation system was simulated using the EPIC model. Representative values of applied depths of irrigation water and N fertilizer amounts were obtained from local reports (CPNRD, 1996). Monthly values of deep-percolation and nitrate leaching were obtained from those simulations.

Table 1: Soil associations found in the study area (from USDA-SCS, 1974)

Association	Name	Texture	Slope
Gibbon-Leshara	Gibbon	Silt loam	nearly level
Platte	Platte	Loamy and sandy	nearly level
Holdrege-Hall-Cozal	Hord	Silt loam	nearly level
Coly-Uly-Holdrege	Coly	Silt loam	gentle to steep
Blendon-Thurman-	Blendon	Sandy loam	nearly level
Valentine			
Wood River	Wood	Silt loam & clay pan	nearly level
	River		

Table 2: Characteristics of crops and irrigation trends found in the study area

Zone	Soil	Crop	Irrigation	% Area	
Upland	Coly	Pasture Others	-	80 20	
Valley	Hord Wood Blendon Gibbon	Corn Soybean Alfalfa	pivot furrow non-irrigated pivot furrow non-irrigated pivot furrow non-irrigated	17 68 0.5 0.5 5 0.5 0.1 2.5	
		Others		4.9	
Floodplain	Platte	Pasture Wet-meadow	non-irrigated non-irrigated	20 65	
		Others	non-irrigated	15	

Intermediate vadose model

The intermediate vadose zone model (IVZM) simulates the transport of deep percolation from the root zone through the vadose zone and predicts the temporal pattern of recharge to the groundwater system. IVZM was developed from a solution of the Richards equation, using the method of decomposition and the Brooks and Corey models (Arumi, 2000). This method produces an approximated analytical solution to predict the residence time of water in the intermediate vadose zone and the rate that water fluxes reach the groundwater. The model estimates the water and nitrate fluxes that enter the saturated zone. A bookkeeping algorithm calculates the monthly recharge of water and nitrate, creating the files used by MODFLOW and MT3D.

The vadose zone near the Nebraska MSEA site consists mainly of the soil association at the surface and the coarse sand of the aquifer (Qs and Qal2, respectively). For each cell of the model a representative vadose zone column was created. The vadose zone depth VZD was estimated using the following index:

$$VZD_{i,j} = Cota_{i,j} - RZD_{i,j} - GWL_{i,j}$$
 (1)

where Cota represents the mean topographic elevation of the cell, the root zone depth is represented by RZD and GWL corresponds to the average value of the groundwater level measured in 1981, 1991 and 1996.

From the geological description of the area (Arumi, 2000), it is possible to estimate the depth of the Qs formation for each cell (DQs). Based on that information the properties of the vadose zone were calculated as:

$$P_{sc} = P_{Qs} \frac{DQs}{VZD} + P_{Qal2} \left[1 - \frac{DQs}{VZD} \right] \quad \text{if DQs} < VZD \tag{2}$$

$$P_{sc} = P_{Os} if DQs > VZD (3)$$

where P_{sc} represents a parameter of the vadose zone, and P_{Qs} and P_{Qal2} are the parameter values for the geological units Qs and Qal2. The parameters considered for each soil association (grouped by Qs geological units) and the coarse sand soil (Qal2) are presented in Table 3.

Table 3: Properties of soil and aquifer materials used for the Vadose Zone Model (based on procedures from Rawls *et al.*, 1992).

Property	Qal2	Qs geological unit				
Brooks and Corey soil parameters	Aquifer coarse sand	Hord silt loam	Wood River silty clay loam	Gibbon silt loam	Blendon sandy loam	Platte loamy sand
Saturated hydraulic conductivity, cm/hr	29.0	0.45	0.30	0.45	2.00	4.50
Saturated water content Residual water content Pore-size distribution Bubbling pressure, cm	0.430 0.045 0.70 7.3	0.45 0.060 0.23 20.7	0.45 0.060 0.23 20.7	0.45 0.060 0.23 20.7	0.45 0.040 0.38 14.6	0.43 0.035 0.55 8.7

The IVZM used the time series of percolation events that was generated for each soil association as input. The model produces the groundwater recharge series needed for the groundwater model. An example of the results obtained from the vadose zone model is shown in Figure 2 for a Hord soil and a vadose zone depth of 3.6 m. The recharge values were organized into the MODFLOW format using an auxiliary program that read results from each series and distributed them through time for each soil association across the groundwater grid.

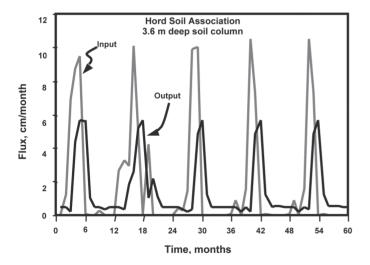


Figure 2: Example of the monthly pattern of inflow into and drainage from the vadose zone as predicted with the soil-plant-water and the intermediate vadose zone models

Calibration and verification of the groundwater model

Calibration of the groundwater model consisted of establishing boundary conditions, determining aquifer properties and defining the effects of the Wood River and the North Channel of the Platte River on the water table. The weather in the Central Platte Valley has a strong

periodicity. The rainy season starts in the spring with April, May and June being the wettest months of the year. Rain extends into the summer but is generally inadequate to fully meet crop water requirements during July and August; thus, irrigation pumping from the aquifer occurs mostly during the last two months of the summer. The soil is frozen during part of the winter which inhibits processes in the upper soil profile. Since there is little extraction from the aguifer outside of the irrigation season the water-table recovers to its highest level in spring. Due to the annual pattern of recharge and pumping, April represents the end of an annual cycle of the groundwater system. Springtime water levels provide a stable time for comparison of trends. Some of the most reliable groundwater level observations for the area were recorded in 1981, 1991 and 1996. Building on the reliability of these data a 10 year calibration period between May 1981 and April 1991, and a 5 year verification period between May 1991 and April 1996 were used in model development and testing.

The natural boundary conditions for the groundwater model are the Platte River on the south and the watershed division on the northwest side of the area. Other boundaries consisted of aquifer cuts that were simulated using the General-Head Boundary module GHB in MODFLOW. This module allows the simulation of variable fluxes across boundaries. The rate of the flux depends on the difference in head between the aquifer h_a and a specified head outside of the model h_e that represents an external source of water:

$$Q = C_d \left(h_e - h_a \right) \tag{4}$$

where C_d is the conductance between the aquifer and the external source of water. This parameter is generated by MODFLOW as a function of the hydraulic conductivity and the geometry of the aquifer.

Calibration of the model was based on external heads, boundary conductance parameters and aquifer parameters. A range of values for the hydraulic conductivity K_s and the specific yield Y was used for each geological unit. The values of K_s and Y were calculated for each cell of the groundwater model depending on the percentage of the geological unit contained in a specific cell. The most important parameter of the model is the hydraulic conductivity for the sand

and gravel aquifer. Previous studies have found that the hydraulic conductivity varies from 40 to 140 m/day. To calibrate the model, we conducted a sensitivity analysis of the groundwater system with respect to the hydraulic conductivity using the root mean of squared residual errors (RMS) as a measure of the goodness of fit. Results of the sensitivity analysis showed that the accuracy of predicted water levels improves for values of K_s over 100 m/day and that there is little difference between the values of 100 and 125 m/day (see Figure 3). These results are consistent with the findings of McGuire and Kilpatrick (1998), thus the hydraulic conductivity of the sand and gravel aquifer was taken as 125 m/day.

The configuration of the water table in Figure 4, shows that the North Channel of the Platte River and the Wood River can be both gaining and loosing streams in this reach. For these reasons, the Platte and the Wood Rivers were simulated as open drains that can lose or gain water from the aquifer depending on the difference between the hydraulic head of the aquifer and the stream. The upland portion of the study area was incorporated into the model to represent the watershed division boundary in the north. Our study focuses primarily on the groundwater system in the Central Platte Valley, specifically that area between the Wood River and the Platte River. For that reason the comparison between simulated and observed data considered only the groundwater model cells located in the Valley.

The groundwater model calibration for the period between May 1981 and April 1991 was used to simulate the observed values in the Valley as shown in Figure 4. The validation of the model for simulation between 1991 and 1996 shows that the results are less accurate around the Wood River, but are still adequate, as observed in Figure 5. The largest mass balance error during calibration was 0.02%. The largest sources of water were the west boundary of the aquifer (62%) and groundwater recharge (7%). The largest sinks of water were the east boundary (57%) and well extraction (36%). The effect of the Platte River is less dominant than that found by McGuire and Kilpatrick (1998). In their work the modeled area was limited by the Wood River on the north and the Platte River on the south. They also used different recharge procedures and boundary conditions.

The Platte River was the most important source/sink of water in their study. The extension of the model to the north and the incorporation of improved recharge estimates and boundary conditions in this study illustrate the importance of agricultural practices and aquifer boundaries on the water balance in the Valley.

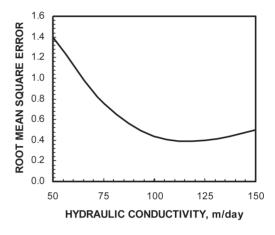


Figure 3: Analysis of the sensitivity of simulated water levels to the hydraulic conductivity of the sand and gravel aquifer.

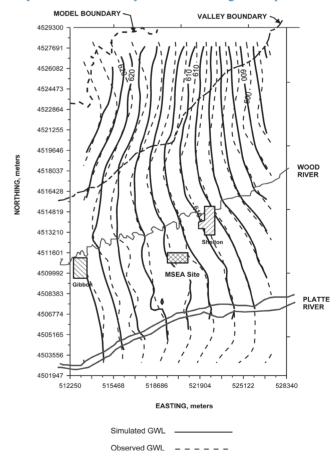


Figure 4: Groundwater levels simulated and observed in April 1991 (elevation in meters above sea level).



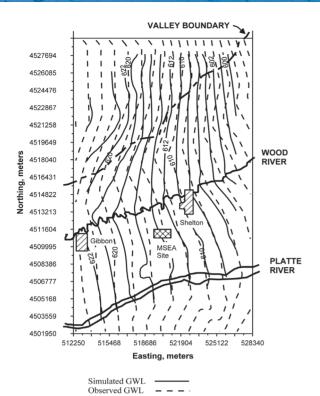


Figure 5: Groundwater levels simulated and observed in April 1996 (elevation in meters above sea level).

Simulation of groundwater flow beneath the MSEA site

Direct sampling of groundwater is the best indication of the integrated effects of management over large areas; however, results may be difficult to interpret for a particular field or farm because of the practice effects on adjacent lands. There may also be delays in improved water quality conditions as a result of management changes. We used two simulation analyses to evaluate the potential groundwater impact caused by localized reduction of nitrate leaching. The first used particle tracking to characterize the aquifer beneath the MSEA site. The second provided an evaluation of groundwater quality changes caused by reductions of nitrate leaching at the MSEA site.

Source region for the MSEA site

Particle tracking has proved to be helpful for determining the direction of groundwater flow. That is important because advection is the main mechanism for solute transport. Snyder *et al.* (1999) used a groundwater flow model with particle tracking to evaluate groundwater vulnerability. They identified recharge areas for the aquifer, and with geographic information systems, determined

characteristics of the recharge areas, down-gradient impacts of land use and the age of the groundwater.

The particle tracking analysis used a sub-model area downstream of the MSEA site to evaluate management effects. The Platte River, the Wood River and the towns of Gibbon and Shelton define the sub-model area. An initial particle tracking analysis was made to identify the pathlines that converge to the MSEA site.

Results

The approach used for the delineation of the MSEA site source region was based on the tracking of five hundred particles over a period of thirty years. Initially, the particles were uniformly distributed in the top of the aquifer, representing the particles that infiltrated directly from crop root zones. Extensive pumping during the irrigation season produces a general trend of particle movement in an east-northeast direction with a gradual vertical movement toward the bottom of the aquifer. The particles that reached the MSEA site, and their initial positions, were registered for each year of the simulation. Using that information, it was possible to calculate the time required for particles to arrive at the MSEA site (called particle age).

Particle age increases with depth as can be seen in Figure 6. Fifty percent of the particles are older than seven years and 25% are older than ten years. The vadose zone in the vicinity of MSEA site is shallow. Recharge residence time in the vadose zone as calculated from IVZM simulations was about two to five months as shown in Figure 7.

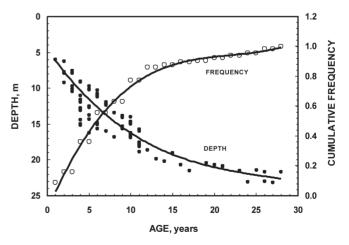


Figure 6: Distribution of particle age with respect to depth in the aquifer beneath the MSEA site.



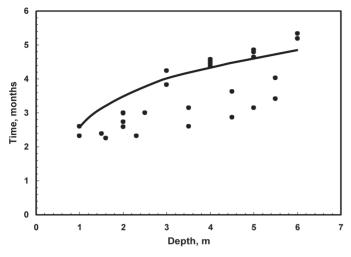


Figure 7: Recharge residence time in the vadose zone near the MSEA site.

The distance that particles traveled from the point where they entered the water table until they reached the MSEA site is shown in Figure 8. The particles at the bottom of the aquifer traveled the greatest distance. About 50% of the particles traveled a distance greater than 1000 m, but only 20% traveled a distance greater than 2000 m. Figure 9 shows that the particle velocity varied between 0.5 and 0.7 m/day in the upper 12 m of the aquifer. The reduction of velocity in the lower part of the aquifer (deeper than 20 m) is caused by a ridge in the confining geological unit (Qal1) that acts as a local barrier to groundwater flow.

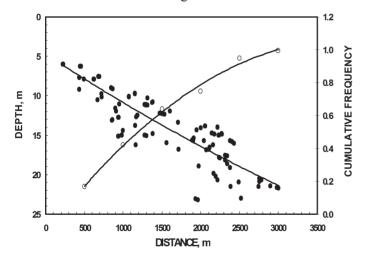


Figure 8: Particle-travel distance distribution with depth

In the Central Platte Valley where furrow irrigation is a common practice, wells are normally located on the upgradient side of each field and are usually screened in the lower third of the aquifer. A significant part of the

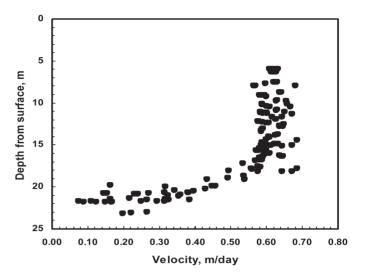
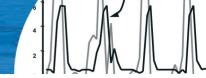


Figure 9: Particle velocity distribution with depth

groundwater that wells can capture has had a much longer residence time than water recently added at the top of the water table. Consequently, the quality of water pumped by a farmer is highly dependent on the management practices of up stream neighbors, since it is primarily related to events that took place over the previous 15 years, and more than 1500 m up-gradient of the irrigation well. Farmers in the CPNRD must analyze and report the NO₂-N concentration of their irrigation water annually. These data have been used to define boundaries of zones in which specific management practices may be required. These zones were initially defined by NO-N concentrations less than 10 mgl⁻¹, in the range from 10 to 20 mgl⁻¹ and more than 20 mgl⁻¹, with increasing restrictions on management practices as concentration increases. The concentration of nitrate in groundwater pumped for irrigation has been used in two ways. First, it is included in computing the nitrogen fertilizer requirement. Nitrogen available from groundwater can reduce fertilizer requirements and reduce the buildup of nitrate in groundwater. Thus, knowing the nitrate concentration of irrigation water is important to management. Secondly, some regulators and producers have assumed that the concentrations measured in producers' wells represent the impact of recent management practices of that producer. That is generally not the case. In this region, zones as far upstream as 1500 m and management practices from the previous 15 years affect the nitrate concentration of a specific well. Our work suggests that groundwater NO-N from irrigation wells may not be useful in identifying farmers whose



recent management practices contribute to contamination problems. Regulatory policies will likely be most effective if they recognize the spatial and temporal dependency of nitrate contamination in groundwater.

Simulating impact of management practices on groundwater quality

The previous analysis suggested that, reductions of nitrate leaching at a field scale could help improve down-gradient groundwater quality. The goal of the second simulation study was to improve our understanding of the effects of field-scale nitrate leaching reduction on groundwater quality. To do that, we compared the simulated changes in NO₃-N concentration of groundwater if nitrate leaching at the MSEA site was reduced to 75, 50 and 25% of the regional average. The study was conducted by applying the model for a ten-year period.

The soils at the MSEA site are mapped within the Hord Soil Association. From the EPIC simulation, the average annual amount of NO₃-N leached from the root zone was estimated as 46 kg/ha. Four 10 year simulations were conducted using the model. Each simulation corresponded to a scenario where the nitrate leaching at the MSEA site was equal to 100, 75, 50 or 25% of the N loss computed with the EPIC model. To quantify changes in groundwater quality, eight "observation wells" were placed within the boundaries of the sub-model (see Figure 1). The wells were arranged in two lines approximately aligned with the groundwater flow.

Results

The computed changes in NO₃-N concentration are shown in Figures 10 and 11. Results from the observation wells along the line from well 1 to well 4 are similar to the pattern from wells 5 to 8. In the top 5 m of the aquifer the NO₃-N concentration is reduced inside the MSEA site (wells 1, 2, 5 and 6). There is some reduction just outside the site at observation wells 3 and 7, and the reduction is negligible at wells 4 and 8 which are further away. The same trend was observed in groundwater which lies between 5 and 10 m below the water table; however, improvements in groundwater quality were less significant in the 5 to 10 m zone compared to the surface layer. In the lower one-third

of the aquifer change is minimal. After 10 years of reduced leaching, groundwater quality is improved in the top of the aquifer, but there is little significant change near the bottom which is consistent with the findings of Spalding *et al.* (2001).

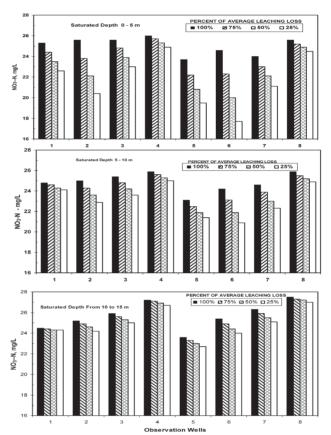


Figure 10: Simulated NO₃-N concentration in surface groundwater layer after 10 years of nitrate leaching at the observation wells.

The change of NO₃-N concentration in the top 5 m of the aquifer at the MSEA site is represented through a series of contour lines in Figure 11. The reduction in groundwater pollution extends to the area immediately down-gradient of the MSEA site. The zone of improved groundwater quality is about twice the size of the MSEA site where management improvements were made to reduce leaching losses to 25% and 50% of the average leaching loss. Obviously groundwater moves relatively slow, thus management impacts are reasonably local with the greatest improvement in groundwater quality taking place directly under the site where nitrate leaching was reduced. While the nitrate concentration in an individual well may not reflect the most recent actions of the producer irrigating that field, the regional groundwater quality is mostly determined by

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local practices. Results show that the groundwater quality is slow to improve and that the quality is the result of practices that occurred in the local area over many years. Improvements in quality will require a widespread, long-term, management control program.

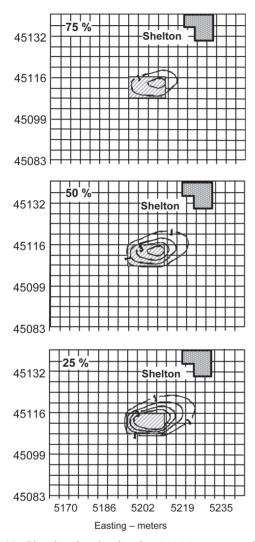


Figure 11: Simulated reduction in NO₃-N concentration in the top 5 m of the aquifer at the MSEA site during a ten-year period, when leaching was reduced to the indicated percent of the regional average. Each contour line represents 1 mgl⁻¹ decrease in concentration.

Conclusions

The combined use of the IVZM, MODFLOW, MT3D and PATH3D models provides a methodology to evaluate the impacts of changes in recharge, nitrate leaching and pumping rates on groundwater quality and quantity. Good characterization of the groundwater system, including the vadose zone, is essential. A common practice in

groundwater modeling is to use recharge rates to calibrate the model. However, this limits the possibility of evaluating effects produced by changes in management of irrigation, N fertilizer and other cultural practices. For that reason, evaluation of agricultural management practices on groundwater should include a root-zone model that estimates nitrate leaching, irrigation pumping and water percolation. It is also necessary to evaluate the effect of the vadose zone. For example, near the MSEA site the vadose zone depth varies between 0 to 6 m and consists predominately of coarse sand. The residence time in the vadose zone there averages about four to six months, which would have little effect on multi-year analyses. In contrast, in deeper and finer soils such as the Coly series in the northern portion of the model area, the effect of the vadose zone is significant and should be considered.

The only indications farmers have of the groundwater quality under their fields are samples taken from their irrigation wells. However, such samples are not good indicators of the effect of individual farmer's management on nitrate leaching and groundwater contamination. In the Central Platte Valley, high-capacity irrigation wells capture water primarily from the lower part of the aquifer. Water samples from irrigation wells represent the effects of management decisions made up-gradient from the well from one to more than fifteen years in the past.

The direct impact of leaching from a single field has a scale comparable with field size. Spalding *et al.* (2001) found that changing from furrow to center pivot irrigation, and adjusting the timing and amount of N fertilizer applications according to need as indicated by crop condition, reduced the nitrate concentration in the upper groundwater beneath a 13.6 ha field at the MSEA site. Our study also indicates that reduction in nitrate leaching at the field scale initially improves water quality in the upper part of the groundwater beneath the field. Subsequently, these changes slowly propagate down-gradient and toward the bottom of the aquifer.

Good management of irrigation and N fertilization can help protect the groundwater quality of a specific area. However, regional groundwater quality changes will require widespread adoption of improved management



practices by most producers. An individual producer who persists with excessive applications of water and N fertilizer will continue to contaminate the irrigation water pumped to his down-gradient neighbors even though they use improved practices. The majority of farmers respond well to educational programs that clearly define the causes and costs of groundwater nitrate contamination and which provide cost effective management alternatives. Unfortunately, there are a few that refuse to make management adjustments. The groundwater management program implemented in 1987 by the CPNRD included both producer education and regulation of management practices. This has proved to be a useful approach to obtaining long-term improvement of groundwater quality in a region of intensive agricultural production like the Central Platte Valley. In most areas within the district groundwater nitrate concentrations have slowly begun to reverse the 40 year upward trend.

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