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Journal Article 1996 WWRC-96-07

Journal of Environmental Quality 25(3):411-418

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1996

WWRC-96-07

Reprinted from the *Journal of Environmental Quality*
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ABSTRACT

A geographic information system (GIS) was utilized to apply a modified DRASTIC method to the assessment of groundwater contamination sensitivity in Goshen County, Wyoming. Several basic environmental characteristics, identified as influencing contaminant transport through the vadose zone to groundwater systems, were mapped, automated, and analyzed. These characteristics include: depth to groundwater, net recharge, hydrogeologic setting, vadose zone soil properties, land surface slope, and saturated hydraulic conductivity. Sensitivity ratings were developed for each parameter based on a combination of mathematical functions and the inherent capacity of each characteristic to influence transport of contaminants. A raster-based overlay analysis was performed to derive a map that portrays cumulative aquifer sensitivity ratings across the county, providing a relative indication of groundwater vulnerability to contamination. A process-based numerical model was used to simulate water flow and solute transport in the vadose zone and groundwater systems. The model incorporated soil and hydraulic properties produced with the GIS into the simulations. Numerical simulations described the time and spatial distributions of contaminants. Chemical mass stored in the soil and leaching out from the vadose zone were computed to characterize groundwater contamination. Groundwater sensitivity indexes, which were developed based on the numerical modeling results, were compared with the GIS sensitivity map and used to verify the reliability of the map.

THE THREAT of groundwater contamination is a major concern of the public. The public is keenly aware that in using, storing, and disposing certain chemicals, pesticides, petroleum products, and sewage, groundwater resources are potentially at risk. Local, state, and federal institutions have begun addressing the public's concerns for preserving a high quality of groundwater. In Goshen County, Wyoming, the groundwater supply for the city of Torrington has been affected by nitrate contamination. Therefore, this study was undertaken to help to understand the groundwater environment in Goshen County and its vulnerability to potential contamination.

> In recognition of the need for effective and efficient methods for protecting ground water resources from future contamination, scientists and resource managers have sought to develop techniques for predicting which areas are more likely than others to become contaminated as a result of activities at or near the land surface . . . (NRC, 1993).

Today this concept has been widely termed *groundwater vulnerability to contamination*, referring to contamination resulting from nonpoint sources or areally distributed point sources of pollution (NRC, 1993).

The USEPA has collectively identified groundwater vulnerability determination methods as one of four primary approaches to assessing groundwater resources for statewide groundwater protection and management. The three other approaches include aquifer sensitivity, aquifer use, and land use assessment. Groundwater vulnerability assessment combines these three approaches, essentially evaluating aquifer sensitivity conditions for a region relative to current groundwater withdrawals, groundwater use, land cover, and land utilization (USEPA, 1993).

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Published in J. Environ. Qual. 25:411-418 (1996).

Abbreviations: GIS, geographic information system; WSEO, Wyoming State Engineer Office; BMP, best management practices.

Due to the wide range of definitions found in the literature, a distinction should be made between aquifer sensitivity and groundwater vulnerability as they apply to this study. Following the USEPA interpretation, aquifer sensitivity may be defined as:

> . . . the relative ease with which a contaminant applied on or near the surface can migrate to the aquifer of interest. Aquifer sensitivity is a function of the intrinsic characteristics of the geologic materials in question and the overlying saturated and unsaturated materials. Aquifer sensitivity is not dependent on land use and contaminant characteristics. [Groundwater vulnerability refers to] . . . the relative ease with which a contaminant applied on or near the land surface can migrate to the aquifer of interest under a given set of land-use management practices, contaminant characteristics, and aquifer sensitivity conditions (USEPA, 1993, p. 125).

A wide range of approaches for predicting aquifer sensitivity and groundwater vulnerability have been developed based on identified factors affecting transportation of contaminants introduced at or near the surface. These methods fall into three major classes: (i) overlay/index methods, which combine specific physical characteristics that affect vulnerability, often giving a numerical score, (ii) process-based methods consisting of mathematical models that approximate the behavior of substances in the subsurface environment, and (iii) statistical methods that draw associations with areas where contamination has occurred (NRC, 1993). This study focused on two of the methods: overlay/index method and process-based modeling.

The unsaturated zone of the soil, or the vadose zone, plays an inextricable role in many aspects of hydrology, including runoff, infiltration, soil water storage, chemical transport, evaporation, plant root uptake, and groundwater recharge. Interest in the vadose zone has dramatically increased in recent years because of growing concern that the quality of soils and groundwater is being adversely affected by agricultural, industrial, and municipal contaminants. Since the vadose zone is an integral part of the hydrological cycle, it is essential to understand the physical and chemical processes in the zone for groundwater protection and management. As advanced computation methods are developed, numerical models are increasingly becoming efficient and economical tools for studying subsurface transport processes (Bresler and Hanks, 1969; Sudicky and Huyakorn, 1991).

The objectives of this paper were first to develop a set of base maps using GIS for Goshen County, Wyoming, describing the relative sensitivity and vulnerability of the groundwater to contaminants. Numerical simulations were then used to model water flow and chemical transport in the vadose zone related to groundwater contamination. Finally, the simulation results were used to develop groundwater sensitivity indexes and compared with the GIS-generated maps.

METHODOLOGY

The study area for this research was Goshen County, in southeastern Wyoming. The pilot study area for a statewide groundwater vulnerability mapping effort, Goshen County was chosen in part due to the intensity of row cropping and associated high levels of agricultural chemical applications, as compared with other counties in the state. Further, Goshen County has experienced nitrate groundwater contamination problems in the Torrington area along the North Platte River.

Aquifer Sensitivity and Groundwater Vulnerability Mapping

Aquifer sensitivity and groundwater vulnerability overlay/index methods fall under two broad categories: (i) hydrogeologic setting classifications, and (ii) scoring methods (USEPA, 1993). The overlay/index procedure, utilized for creating the sensitivity and vulnerability maps in this study is akin to the widely used DRASTIC groundwater pollution hazard (e.g., aquifer sensitivity) assessment method (Aller et al., 1987).

The DRASTIC sensitivity model functions on the basis of the following linear combination equation:

$$\text{Pollution potential} =$$
$$D_rD_w + R_rR_w + A_rA_w + S_rS_w + T_rT_w + I_rI_w + C_rC_w \qquad [1]$$

where D is the depth to groundwater table, R the net recharge, A the aquifer media (geology), S the soil media (texture), T the topography (slope), I the impact of vadose zone, C the hydraulic conductivity of the aquifer, and the subscripts r and w denote the rating and the weight, respectively. Ratings reflect the relative significance of classes (1–10) within each of the seven parameters, while weights provide an indication of relative parameter influence within the equation. All variables are dimensionless.

The aquifer sensitivity and groundwater vulnerability mapping procedures carried out in this study incorporated the use of a Geographic Information System (GIS). A GIS is a computerized mapping and spatial data analysis system, which enables the manipulation and analysis of spatially referenced information to describe the relationship between landscape features. Though not originally designed as a GIS-based tool, the DRASTIC model lends itself to such an implementation (Merchant, 1994). GIS applications of the DRASTIC model (Merchant et al., 1987; Griner, 1989; Regan, 1990; Evans and Myers, 1990; Rundquist et al., 1991; Trent, 1993) and its variations (Riggle and Schmidt, 1991; Lusch et al., 1992) have been widely documented in the literature.

The GIS was used in a number of procedures, including: (i) converting hardcopy map information into a digital format, (ii) creating a map of groundwater depth from well log water depth records and well location information, (iii) creating a map of the saturated hydraulic conductivity from well log pumping data and well location information, (iv) assigning sensitivity rating values to mapped attribute values, and (v) combining or overlaying individual characteristic maps to create the final cumulative sensitivity and vulnerability maps.

While following DRASTIC's linear combination design, the Wyoming sensitivity procedure differs in a number of key aspects. First, the Wyoming procedure incorporates different mapping layers than DRASTIC. While DRASTIC uses map layers for the vadose and saturated materials, this study incorporates these two layers into a more comprehensive geohydrologic mapping unit. Second, the Wyoming procedure does not adhere to the DRASTIC method for assigning rating values to predefined map classes. A new rating system has been developed that uniquely reflects Wyoming's hydrogeologic environment and landscape characteristics influencing contaminant transport. Third, the Wyoming procedure applies a weighting value of 1.0 to each of the individual ratings maps, assuming the magnitude of each parameter rating is equal. Now the DRASTIC sensitivity model becomes:

Pollution potential =

$$D_r + R_r + A_r + S_r + T_r + I_r + C_r \quad [2]$$

We recognize that the potential exists, in certain situations, for one parameter's characteristics to override another. However, during model development, the decision was made, at the request of the Wyoming Department of Environmental Quality, to omit variable weights. The rationale behind the decision was that weighting involves a certain degree of subjectivity, which would best be left to the regulatory agency identified as the principal user of the analyses. Finally, groundwater vulnerability in the Wyoming study is accounted for by integrating a rating map of irrigation related recharge with the final sensitivity map.

Aquifer sensitivity mapping requires consideration of the hydrogeologic environment and the surrounding landscape characteristics that influence the transport of potentially available contaminants from or near the ground surface into and through an aquifer. An aquifer sensitivity map describes the inherent capacity of the terrestrial and underground environments to transport available pollutants. Aquifer sensitivity mapping in Wyoming was carried out by identifying six key environmental/landscape characteristics that influence the contaminant transport from the surface through soil and geological media into and through an aquifer. These mappable characteristics include (i) depth to groundwater, (ii) net annual aquifer recharge, (iii) geohydrologic environment of the groundwater, (iv) soils, (v) land slope, and (vi) aquifer hydraulic conductivity. For each of these base maps, ratings are assigned to the descriptive map classes relating the capacity of that environmental characteristic to influence the contaminant movement to the groundwater. The final sensitivity map was created by superimposing the six individual rating maps and summing the rating values. The ratings of the final sensitivity map reflect the contribution of each individual map layer. Higher ratings depict areas where the groundwater is inherently sensitive to pollutant contamination. Abridged from Hamerlinck (1996), an overview follows of the methods employed in creating and integrating the digital characteristic data layers.

Depth to groundwater is a significant factor controlling the ability of pollutants to reach the aquifer. The closer the groundwater is to the land surface, the faster water-transported contaminants can reach the aquifer. In addition, the shorter the travel distance through the vadose zone, the less contact time there is between contaminants and chemical attenuating materials. Conversely, the greater the depth to water the less sensitive the aquifer is to contamination. Depth to groundwater data was collected from well log permit records of Wyoming State Engineer Office (SEO). In total, 1288 well records were utilized in Goshen County for estimating depth to first encountered groundwater. To minimize the effect of variations in water levels over time, wells and their associated water level data were chosen from the most recent SEO driller logs (e.g., within the last 3-5 yr). Unfortunately, while time of year also is a factor in recorded water depths, data availability constraints prevented isolating water level data within a specific time of year. Well locations were digitized at the center of individual/Township/Range sections with the GIS with corresponding water depth and required well log attribute information entered into the GIS database. Ordinary kriging (Burgess and Webster, 1989) was applied to generate a map of the groundwater depth for the county. Assigning a sensitivity rating to the water depths was achieved by defining a set of functions relating water depth to a sensitivity rating.

Recharge represents the primary contaminant transport mechanism into the aquifer. Net recharge describes the amount of water available at the surface that infiltrates into the soil, then continues to percolate through the vadose zone into the groundwater. The calculation of net recharge was based on a number of factors, including precipitation, snow melt, and evaporation (Hamerlinck, 1996). Irrigation and other artificial water application methods were accounted for in the groundwater vulnerability map.

Geologic variables of primary importance are those that influence ingress into and circulation of fluids within a given body of rock. Potential sensitivity for contamination is therefore primarily a function of the permeability characteristics of the rock unit. Four geologic attributes were identified as important: (i) rock type, (ii) imprinted permeability structure, (iii) structural character of the rock body, and (iv) regional tectonic setting. These were arranged in a progression from micro to macro in geologic scale. Within each attribute, the entries were ranked on a relative scale of 1 to 10, wherein a higher number indicates a greater potential for contamination. Because the four attributes were assumed to be independent variables, no single attribute takes hierarchial preference over another. As a pilot study for a statewide effort, the vulnerability mapping method developed for Goshen County continues to evolve. One result of this iterative process was the identified potential for interdependency among the geologic variables discussed above. As a result, the characterization of this parameter is being revised (P.W. Huntoon, 1995, unpublished data).

A number of soil characteristics control the capacity of contaminants to move into the groundwater. The thickness of soils determines the length of time contaminants reside within the media. The longer the contact time, the more opportunity for interaction with biological and physical elements that can potentially degrade pollutants. Organic material, clays, and other minerals react with contaminants to degrade, absorb, or volatilize the chemicals. The soil hydraulic conductivity, texture, and structure influence the rate at which water percolates through the soil profile. Soil types are strongly controlled by the surface deposits and morphology. This relationship is sufficiently consistent so that boundaries of surficial geology units can be considered the same as those of contrasting soil types. The USDA Goshen County Soil Surveys were used to evaluate soil composition and landscape relationships. Sensitivity ratings were assigned to define soils classes based primarily on the texture and thickness of the soils. Rockiness and depth to bedrock were also considered in the rating.

Land surface slope affects the amount of water and contaminants available at the surface for infiltration into the soil and potentially into the groundwater. The flatter the slope, the longer water resides in one place on the land surface, and the greater the chance for infiltration. A land slope map for Goshen County was generated from 1:100 000 scale USGS topographic map elevation contour lines. The contour lines were scanned into the GIS and converted to a cell-based slope map. Sensitivity ratings were assigned to the slope map by defining a set of functions that describe how percent slope influences potential groundwater contamination (Hamerlinck, 1996). The GIS was used to convert slope values to ratings by processing slope data through the defined functions.

The saturated hydraulic conductivity of the aquifer describes the rate at which water moves through the aquifer. Geologic media composed of coarser materials, such as unconsolidated sands and gravels, have high conductivity values. Consolidated materials with significant fracturing will also allow free movement of water through the geologic media, and thus have higher conductivity values. Consolidated materials with minimal fracturing have low conductivity values. Groundwater sensitivity is related to the saturated conductivity through the aquifer's capacity of transporting pollutants away from the point at which they enter the aquifer. The greater the saturated conductivity, the farther contaminants will travel and potentially contaminate ever greater volumes of groundwater. A saturated material thickness map for the North Platte River Valley developed by the USGS (Christ, 1975) was input for the GIS. A saturated conductivity map was generated by dividing the available transmissivity by the saturated thickness. The remaining upland areas of the county and small stream alluvial materials were assigned conductivity values based on transmissivity calculations from representative well log pumping records, and estimated saturated thicknesses for the aquifers at well locations. Conductivity values were then extrapolated to similar aquifers across the county. Sensitivity ratings for the conductivity were assigned by using functions describing the relationship between a conductivity value and a sensitivity rating (Hamerlinck, 1996).

The groundwater vulnerability map was generated by combining the final aquifer sensitivity map with a map of irrigated croplands. The irrigation map represents areas where the natural hydrologic system has been modified and where there is intensive use of agricultural chemicals. Ratings were assigned to the irrigated cropland maps relating the capacity of irrigation water to enhance the transport of agricultural chemicals to the groundwater.

Numerical Modeling

The governing equation for one-dimensional, vertical flow in soils is:

$$C\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left(K\frac{\partial h}{\partial z} - K\right) \quad [3]$$

where h is the pressure head; $C = d\theta/dh$ is the soil water capacity in which θ the volumetric water content; K is the hydraulic conductivity; z is soil depth, assumed to increase in the downward direction; and t is time.

In this study, the initial condition is given in terms of the pressure head at the equilibrium, i.e.,

$$h(z,0) = z - z_0 \quad [4]$$

where z_0 is the groundwater depth.

A second-type boundary condition is imposed at the soil surface ($z = 0$):

$$\left(-K\frac{\partial h}{\partial z} + K\right)\Bigg|_{z=0} = q_0(t) \quad [5]$$

where $q_0(t)$ is the prescribed net fluid flux. The lower soil boundary condition at the groundwater table ($z = z_0$) is

$$h(z_0,t) = 0 \quad [6]$$

The soil hydraulic properties, $\theta(h)$ and $K(\theta)$, are assumed to be described by the parametric functions of van Genuchten (1980):

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{(1 + |\alpha h|^n)^m} \quad [7]$$

$$K(S_e) = K_s S_e^{1/2}\,[1 - (1 - S_e^{1/m})^m]^2 \quad [8]$$

in which S_e is relative saturation:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad [9]$$

and

$$m = 1 - 1/n \quad [10]$$

where θ_s is the saturated water content, θ_r is the residual water content, K_s is the saturated hydraulic conductivity, and α and n are shape parameters.

Transport of miscible components is described by the convection–dispersion equation

$$\frac{\partial \theta c}{\partial t} = \frac{\partial}{\partial z}\left(\theta D\frac{\partial c}{\partial z}\right) - \frac{\partial qc}{\partial z} \quad [11]$$

where c is the solute concentration in solution, D is the dispersion coefficient, and q is the Darcian flux density. The dispersion coefficient is defined as

$$D = \varepsilon|v| \quad [12]$$

where ε is the dispersivity of the medium, and $v = q/\theta$ is the average pore water velocity.

A third-type or flux-type boundary condition is specified at the soil surface

$$\left(-\theta D\frac{\partial c}{\partial z} + qc\right)\Bigg|_{z=0} = q_0 c_0 \quad [13]$$

where c_0 is the concentration of the infiltrating water, and q_0 is the Darcian flux at the soil surface. A zero gradient boundary condition at $z = z_0$ is used during periods of drainage:

$$\frac{\partial c}{\partial z}\Bigg|_{z=z_0} = 0 \quad [14]$$

The governing equations of water flow and chemical transport with the specified initial and boundary conditions were solved using the finite element method implemented in the numerical model, HYDRUS (Vogel et al., 1995). At each location, water and chemical movement from the soil surface to the groundwater table was considered as a one-dimensional transport process. HYDRUS was used to simulate water flow and chemical transport in the vadose zone and to calculate chemical distributions in the soil and the chemical mass leaching out to the groundwater.

RESULTS

Sensitivity and Vulnerability Mapping

By following the procedures discussed in the previous section, six rating maps were created for the depth to groundwater, net annual water recharge, the geohydrologic environment of the groundwater, soils, land slope, and the aquifer hydraulic conductivity, respectively. The sensitivity map was a product of the six individual rating maps constructed using GIS techniques. The resulting range of groundwater sensitivity rating values extended from 12 to 54, with the lowest possible rating being 6 and the highest rating being 60. Five classes of relative sensitivity (1-5) were chosen to display the range of sensitivity values: low, medium-low, medium, medium-high, and high groundwater sensitivity (Fig. 1). These classes were chosen based on a review of the final sensitivity map's histogram. The histogram displays the total area in the county assigned to each sensitivity rating value. It resulted in a positively skewed, bimodal distribution. Classes were delineated to encompass the multiple peaks reflecting the natural groupings of ratings. The high

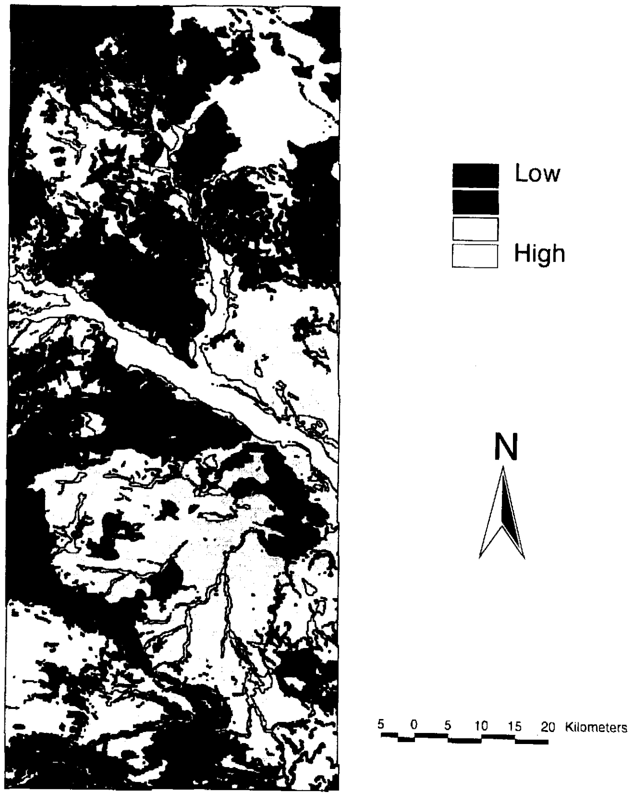

Fig. 1. Map of the aquifer sensitivity rating.

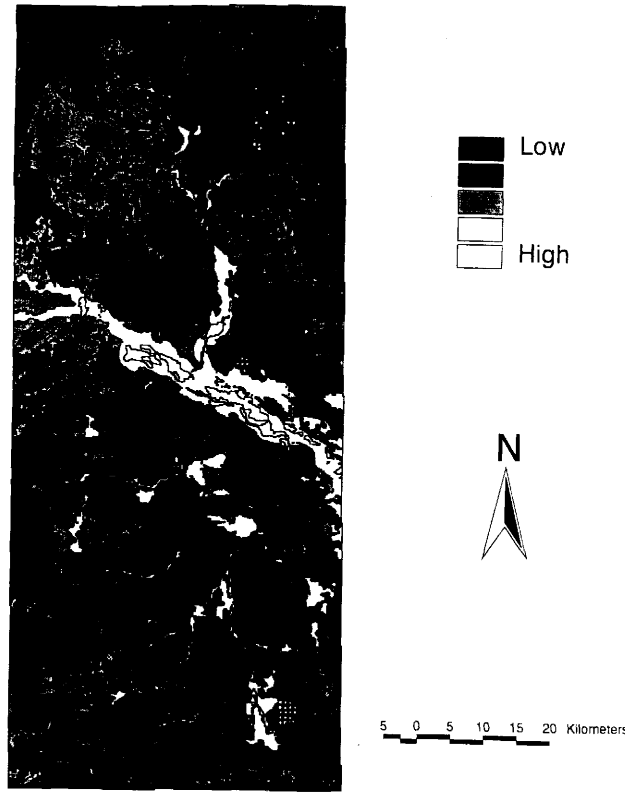

Fig. 2. Map of the groundwater vulnerability rating.

sensitivity areas were located primarily in the alluvial material adjacent to rivers, streams, and lakes. The combination of very shallow groundwater depths, a deep layer of saturated material, very porous soils and geologic medium, and extremely flat lands led to this high ranking. Medium-high ranked lands generally extended outward from the highly rated lands. These lands were primarily found situated in alluvial materials. The lower rating was due to an increasingly deeper groundwater table, a smaller saturated media thickness, and more mature soils exhibiting greater clay and organic matter content. Medium-low ratings reflected the majority of the upland areas in Goshen County as well as elevated ridges throughout the Goshen Hole. Depth to groundwater deepened significantly and slopes in the rolling landscape increased. Below the thin layers of clay loam and loamy textured soils, prohibitive layers of hardpan and shallow bedrock existed. Areas rated with low sensitivity were upland areas with ever-increasing depth to groundwater, diminished hydraulic conductivities, and very steep slopes.

The vulnerability map (Fig. 1) was generated by adding or combining the final sensitivity map with an irrigation recharge rating map using GIS grid overlay techniques. The vulnerability rating values range from 17 to 63, resulting in a positive skewed bimodal distribution. Five classes of vulnerability indexes (1–5) representing low, medium-low, medium, medium-high, and high groundwater vulnerability (Fig. 2) were chosen to maintain consistency with the sensitivity map. The high vulnerability ratings represented a combination of irrigated cropland located on highly sensitive land of the North Platte River and Rawhide Creek valleys and land found directly adjacent to perennial streams. Medium-high vulnerability lands were situated on high and medium-high sensitive lands where there were no irrigated crops, such as the sand dune areas and alluvial fill areas within the North Platte River and Rawhide Creek valleys. Medium-high vulnerability areas were also found where medium-high and medium sensitivity rated lands coincided with irrigated agriculture, such as those found on river terraces north of the North Platte River Valley, the lowland area south of Hawk Springs Reservoir, and center pivot irrigation circles located throughout the upland regions on sandy soils. Medium vulnerability lands were identified in sandy eolian deposits without irrigation agriculture, as well as in low-lying irrigated and nonirrigated areas throughout the Goshen Hole. Medium-low and low vulnerability areas corresponded directly with the medium-low and low sensitivity lands on the sensitivity map.

Numerical Modeling

Using HYDRUS, we simulated 130 locations randomly distributed in Goshen County. At these locations, information exported from the GIS, including aquifer hydraulic conductivity, water recharge, groundwater depth, and soil texture, was used as input for the numerical simulations. Since the saturated hydraulic conductiv-

Table 1. Parameters of soil hydraulic functions.

Soil texture	θ_r	θ_s	α (1/cm)	n	K_s (cm/d)
Clay	0.07	0.38	0.008	1.10	4.80
Silt loam	0.067	0.45	0.020	1.41	10.80
Loam	0.078	0.43	0.036	1.56	24.96
Fine sandy loam	0.065	0.41	0.075	1.89	106.10
Loamy sand	0.057	0.41	0.124	2.28	350.20
Sand	0.045	0.43	0.145	2.68	712.80

ity in the vadose zone was not available, we chose the parameter mainly based on the soil texture (Carsel and Parrish, 1988) as shown in Table 1. Meanwhile, the saturated hydraulic conductivity of the aquifer was used as additional information for determining the saturated hydraulic conductivity of the vadose zone. The range of the saturated soil hydraulic conductivity was from 8 to 804 cm/d and the groundwater depths ranged from 0.5 to 60 m. At each location, the soil was treated as one-dimensional profile from the surface to the groundwater table. Water recharge with a concentration of 10 mg/L was used as the input flux at the soil surface and a 100-d simulation was conducted. Soil hydraulic property functions were estimated based on the soil texture and parameter values of θ_r, θ_s, α, and n were chosen according to Carsel and Parrish (1988) as shown in Table 1. The parameters may also be constructed from the soil texture using pedotransfer functions (Wösten and van Genuchten, 1988).

Figure 3 shows the simulated relative concentration at the groundwater table vs. time for a clay soil and a sandy soil. The concentration reached the maximum value within 50 d for the sandy soil, while it took more than 100 d for the relative concentration in the clay soil to reach 70%. The groundwater depth affects water flow and solute transport in the vadose zone. The concentration profiles in the vadose zone with groundwater depths 10 and 30 m are shown in Fig. 4A, while relationships between the relative concentration at the groundwater depths vs. time are presented in Fig. 4B. Simulations were conducted to investigate the effect of other factors on water flow and chemical transport in the vadose zone and on groundwater contamination. The factors considered included the infiltration water rate at the surface, patterns of rainfall and irrigation, root uptake, initial concentration and distribution of chemicals, and others.

To develop relative indexes for characterizing groundwater contamination, we used an infiltration rate 15 cm/d and a concentration of 10 mg/L for 100-d simulations at the 130 locations. Output results from the simulations included the cumulative water flux reaching the groundwater table since start of simulation (TDRAIN), total amount of water present in the soil (STORW), cumulative amount of solute leached from the soil profile to the groundwater since start of simulation (SLTOUT), and the starting time of groundwater contamination (TSB). The TSB was characterized by the time when the concentration leaching to the groundwater table reached 5% of the input concentration. Based on the

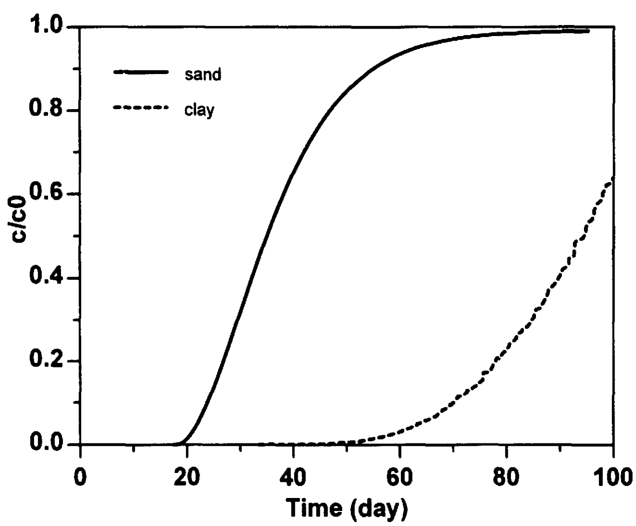

Fig. 3. Simulated relative concentration at the groundwater table vs. time for a clay soil and a sandy soil. z_0 = 10 m, q_0 = 4.5 cm/d and soil hydraulic parameters were taken from Table 1.

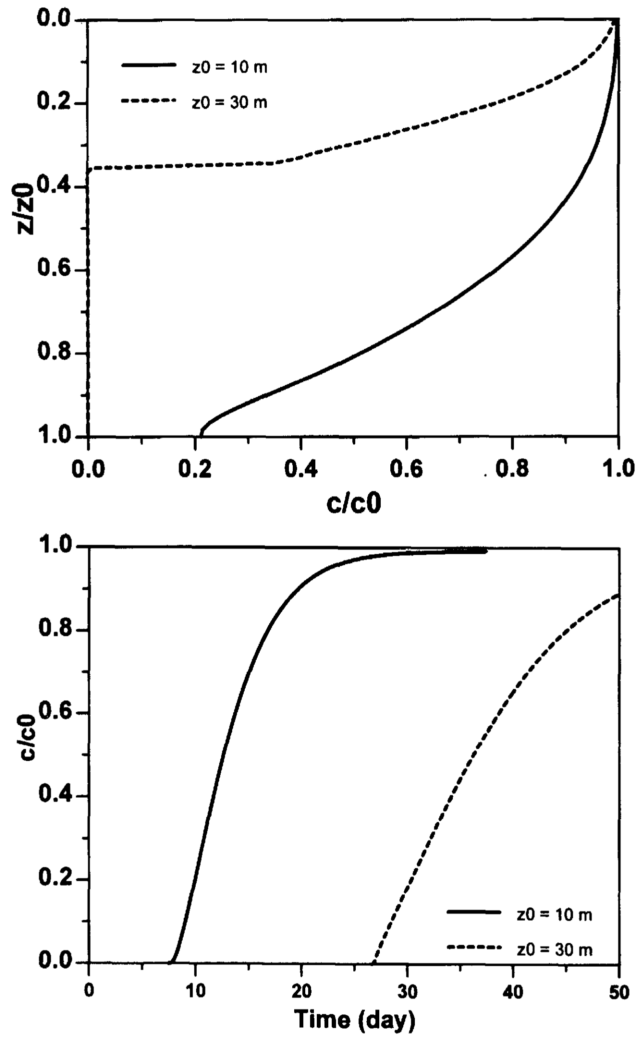

Fig. 4. (*A*) Concentration profiles in the vadose zone at t = 10 d and (*B*) relationships between the relative concentration at the groundwater table, with groundwater depths 10 and 30 m in sandy soils. The soil hydraulic parameters were taken from Table 1 and q_0 = 15 cm/d.

results of SLTOUT and TSB, we developed groundwater sensitivity indexes as shown in Table 2. Sensitivity maps generated from the GIS index (Fig. 5A) and SLTOUT index (Fig. 5B) were comparable, especially in the highly sensible regions. The correlation coefficient between the GIS index and SLTOUT index was 0.86 and it was as high as 0.95 in the highly sensible regions with sensitivity indexes 4 and 5. Combinations of the simulation results, such as ln(LSTOUT/TSB) and ln(LSTOUT/TSB/STORW), may also be used to develop groundwater sensitivity indexes.

DISCUSSION AND CONCLUSIONS

The aquifer sensitivity map of Goshen County was developed using the GIS mapping and numerical modeling methods. This map reflected an aquifer's inherent capacity to become contaminated. A high sensitivity index indicates the capacity of the hydrogeologic environment and the landscape factors to readily move waterborne contaminants into the groundwater. Low ratings represent groundwater that is better protected from contaminant leaching by the natural environment.

Both the GIS-based sensitivity and vulnerability maps portray a relative ranking of potential groundwater contamination. As an ordinal representation, the maps lack specificity. The sensitivity and vulnerability maps must only be used as a relative indicator of groundwater sensitivity/vulnerability at one location as compared with another. The scale at which mapping occurs also limits the locational specificity of the final maps. The 1:100 000 mapping scale will miss localized derivations found within a larger hydrogeological landscape pattern of the sensitivity map. The scale of mapping also influences the accuracy of the vulnerability map. At a 1:100 000 scale small parcels of agricultural land will be omitted from the map and nonagricultural lands will be included.

The GIS mapping used six basic environmental characteristics – depth to groundwater, net recharge, hydrogeologic units, vadose zone soil properties, land surface slope, and saturated hydraulic conductivity of aquifer – to develop groundwater sensitivity indexes. The numerical modeling utilized the depth to groundwater, vadose zone soil properties, and the soil saturated hydraulic conductivity for the sensitivity index development. Both methods provided comparable results, and an excellent agreement was obtained in the high sensibility regions. The main discrepancy of the two methods may be caused by the lack of available information about the saturated hydraulic conductivity in the vadose zone, which is the key parameter for the numerical modeling processes. While GIS provides an efficient way for large-area mapping, the

Table 2. Sensitivity indexes based on cumulative amount of solute leached from the soil profile to the groundwater (SLTOUT) and the starting time of groundwater contamination (TSB).

SLTOUT (mg)	TSB (day)	Sensitivity index
SLTOUT ≤ 50	TSB ≥ 60	1
50 < SLTOUT ≤ 150	60 > TSB ≥ 45	2
150 < SLTOUT ≤ 250	45 > TSB ≥ 25	3
25 < SLTOUT ≤ 350	25 > TSB ≥ 10	4
SLTOUT > 350	TSB < 10	5

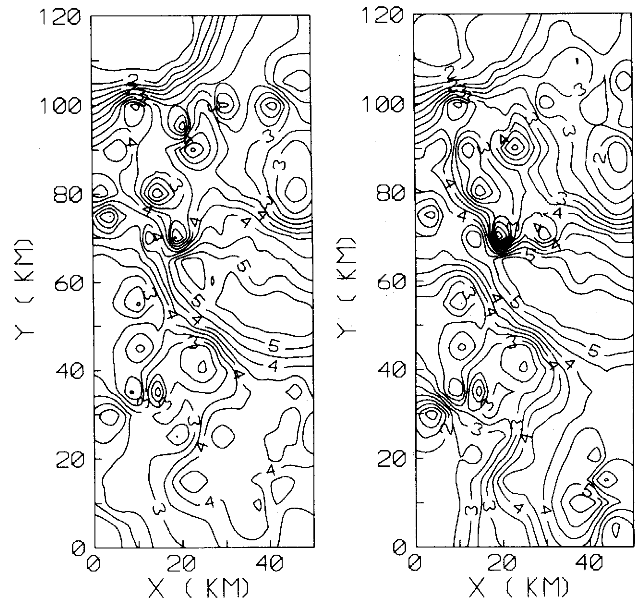

Fig. 5. Sensitivity maps generated from (*A*) the GIS index and (*B*) SLTOUT index.

numerical modeling gives detailed and site-specific results of water flow and solute transport in the vadose zone and groundwater systems. Using numerical simulations and sensitivity analyses of the factors affecting soil and groundwater contamination, we may develop reliable rating functions to be used in the GIS. This research is being conducted.

The groundwater sensitivity and vulnerability maps are an extremely useful tool for many aspects of regional and local groundwater resources planning and management. The vulnerability map can be used to assess contamination related to agricultural activities, whereas the sensitivity map can be used to develop a vulnerability map for other types of contaminant uses and storage (Hamerlinck et al., 1993). The maps can be used for prioritizing areas that require special attention due to potential groundwater contamination. Proactive steps can include groundwater testing to succinctly determine if a groundwater quality problem currently exists, or targeting financial and personnel resources to implement appropriate land management practices to minimize the potential for future contamination. A number of programs can benefit from using the groundwater sensitivity map. These programs include: agriculture best management practices (BMP) targeting wellhead protection programs, leaking underground storage tank programs, underground injection well management programs, and waste disposal citing and management programs.

ACKNOWLEDGMENTS

This research was funded in part by a USEPA grant administered through the Water Quality Division of the Wyoming Department of Environmental Quality, Cheyenne, WY. Digital cartographic assistance in the preparation of this manuscript was provided by Christopher S. Arneson, Wyoming Water Resources Center.

APPENDIX

Symbols Used

D_r = rating of the depth to groundwater table
R_r = rating of net recharge
A_r = rating of aquifer media (geology)
S_r = rating of soil media (texture)
T_r = rating of topography (slope)
I_r = rating of impact of vadose zone
C_r = rating of aquifer hydraulic conductivity
D_w = weight of the depth to groundwater table
R_w = weight of net recharge
A_w = weight of aquifer media (geology)
S_w = weight of soil media (texture)
T_w = weight of topography (slope)
I_w = weight of impact of vadose zone
C_w = weight of aquifer hydraulic conductivity
h = pressure head (cm of water)
C = soil water capacity (per cm)
K = hydraulic conductivity (cm per d)
z = soil depth (cm)
t = time (d)
z_0 = groundwater depth (cm)
q_0 = prescribed net fluid flux (cm per d)
S_e = relative saturation
θ = volumetric water content
θ_s = saturated water content
θ_r = residual water content
K_s = saturated hydraulic conductivity (cm per d)
α = parameter in Eq. [6] (per cm).
n and m = parameters in Eq. [6].
c = solute concentration in solution (mg per L)
D = dispersion coefficient (cm^2 per d)
ε = dispersivity of the medium (cm)
v = average pore water velocity (cm per d)
c_0 = concentration of the infiltrating water (mg per L).

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