VULNERABILITY ASSESSMENTS OF COLORADO GROUND WATER TO NITRATE CONTAMINATION

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Abstract. Nitrate (NO_3-N) contamination of ground water aquifers is an important problem in the United States and throughout the world, particularly as ground water resources become increasingly relied upon to support human needs. Cost effective methodologies are needed to facilitate decision-making for ground water protection. To aid ground water protection organizations, we designed two tools to assess aquifer vulnerability to NO_3-N contamination in Colorado. The first tool is a statewide aquifer vulnerability map (VM) that identifies regions vulnerable to ground water contamination. The VM uses five factors that influence aquifer vulnerability on a regional scale: aquifer locations, depth to water, soil drainage class, land use, and recharge availability. We validated the VM using 576 discrete ground water sample points from throughout the state and found that the VM was able to delineate areas of increased aquifer vulnerability to NO_3-N contamination ($r^2 = 0.78$). The second aquifer assessment tool is a vulnerability matrix (VMX) developed to help practitioners determine relative aquifer vulnerability to NO_3-N contamination on a field scale. The VMX consists of a series of factors that are rated and combined for a particular field. This rating is used to give landowners an index of general aquifer vulnerability to NO_3-N contamination for a specific field, and inform them of changes in management practices to reduce the vulnerability. The VMX can be used in conjunction with the VM to determine NO_3-N contamination potential from intensive agriculture.

Keywords: ground water, nitrate leaching, vulnerability, geographic information systems, GIS

1. Introduction

The protection of ground water resources is a topic of concern throughout the United States (US) and world. In the state of Colorado, located in west central U.S.A., ground water is an important resource as approximately 20% of residents rely on ground water for drinking water supplies. Nitrate (NO_3-N) is a significant contaminant to ground water in many areas (Nolan *et al.*, 1997) and effort is required to minimize future contamination. Nitrate contamination is often associated with anthropogenic activities at the ground surface, such as the fertilization of agricultural crops (Kellogg *et al.*, 1992). Once ground water is contaminated it is difficult to remediate, therefore, preventing contamination is the primary strategy of water quality management agencies.

Due to the extreme spatial variability in the application of nitrogen (N) containing fertilizers, biosolids and manures in Colorado and in the location and quantity of ground water resources, it is impractical to manage N fertilizer inputs uniformly across the state. Certain combinations of land use and hydrogeologic factors cause some areas to be more vulnerable to NO_3-N leaching than others. Vulnerability is commonly defined as the relative ease with which a contaminant can migrate to the aquifer of interest under a given set of agronomic management practices and aquifer sensitivity conditions (U. S. EPA, 1993). Areas where ground water is less vulnerable to NO_3-N contamination may not require the same level of scrutiny and management as areas with high vulnerability.

Both a statewide and a field scale assessment approach are needed in Colorado to address the different spatial scales of interest that might be necessary for implementing source water protection programs and actual on-the-ground management programs. A statewide approach is proposed herein that uses a Geographic Information System (GIS) to combine various spatial data sets into one map of aquifer vulnerability to NO_3-N contamination. Similar studies have been reported by Berg and Abert (1994), Fritch *et al.* (2000a, b), Hall (1998), Hearne *et al.* (1995), Navulur and Engel (1998), Rupert (1999), Secunda *et al*. (1998), and Zhang *et al.* (1996). These studies vary in their methods, scope, and geographical location. However, the majority of these studies concentrated on watershed size areas and few attempts have been made to assess aquifer vulnerability on a statewide scale. Aquifer vulnerability assessments at the statewide scale are intended as screening tools to help delineate vulnerable areas and to aid agencies in allocating resources to protect ground water. General areas identified as having higher aquifer vulnerability can be assessed in more detail using the GIS approach if data is available at the appropriate scale.

A field scale aquifer assessment tool is also proposed that utilizes a series of site-specific factors for a given field to estimate NO_3-N leaching risk. Similar to the Colorado Phosphorus Index Risk Assessment (P-Index) (Sharkoff *et al.*, 2003), each factor is rated; the ratings are then added to determine a final vulnerability index for that field. The vulnerability matrix (VMX) is not intended to determine quantifiable field level N leaching, such as produced by the Nitrate Leaching and Economic Analysis Package (NLEAP) model (Shaffer *et al.*, 1991). Rather, it is intended to quickly determine general vulnerability and may be used to develop planning alternatives and select management practices to minimize the potential for NO_3-N leaching to underlying aquifers. A more thorough analysis is needed if land managers wish to quantify leaching risk associated with management factors.

The purpose of this investigation was to develop two separate methodologies to evaluate the vulnerability of ground water aquifers in Colorado to NO_3-N contamination. The specific objectives of this study were to: (1) develop a statewide map of aquifer vulnerability to NO_3-N contamination for Colorado's major ground water resources; and (2) develop a simple field scale NO_3-N VMX to be used by landowners to help determine the potential risk of ground water contamination by NO_3-N as a result of field specific conditions. The vulnerability scores obtained from these tools were compared to actual ground water and field data from Colorado to qualitatively assess the validity of the developed products. This screening approach could be effectively applied to other geographical regions throughout the US and world.

2. Methods

2.1. Vulnerability map spatial data development

All available spatial land use and hydrogeologic data that were reliable, relevant, and covered the entire state were considered for inclusion when developing the vulnerability map (VM). There is some uncertainty associated with spatial data utilized on a statewide scale, however, this uncertainty is acceptable when it is understood that a map of this scale is not designed to delineate exact locations, but rather to define general areas of varying vulnerability. From the available data that met the criteria, five factors were selected, each comprising a map layer in the GIS. We created the final VM by using a map equation to combine input factors together using ArcView and ArcInfo GIS software (ESRI, 2001). All layers were developed at a grid resolution of 1000 m^2 and were converted to Albers equal area projection. The five map factors that were used to assess primary aquifer NO_3-N vulnerability included location of primary aquifers, depth to ground water, soil drainage class, recharge availability, and land use.

Location of primary aquifers: To determine aquifer vulnerability to NO_3-N pollution for the statewide map, it was necessary to define the aquifers of interest. Areas overlying primary (high-productivity) aquifers are critical to protect as they typically supply water to larger populations. Thus, the presence or absence of one or more primary aquifers was selected as an indicator of key ground water resources needing protection. We used an aquifer map developed by Hall (1998) who created the map of aquifer extent from digitized geologic maps and published reports of aquifer extent. Areas overlying a primary aquifer were assigned a value of 1; all other areas were assigned a value of 0 (Table IA). This does not mean that areas not underlain by a primary aquifer cannot be vulnerable to NO_3-N contamination; it means at this time there is insufficient aquifer data for these areas to allow

TABLE IA
Vulnerability map layers: aquifer extent definition

Range of values	Description	Interpretation
0	Overlying a principal, high conductivity aquifer	More vulnerable
1	Overlying low conductivity materials	Less vulnerable

vulnerability assessment. This limitation could be addressed when improved aquifer data becomes available in the future.

Depth to ground water: Depth to ground water affects the length of time required for NO_3-N to reach the ground water and thus in some cases, the N concentration of the leachate. The depth to ground water map for Colorado was developed by Hall (1998) from published reports of well measurements and well logs. Where available, ground water and water table elevation data were digitized from published maps (Figure 1). Depths to ground water are divided into three categories (Table IB). These categories are wide enough to capture ground water vulnerability on a regional scale. Rupert (1999) found that large categories in depth to ground water were statistically significant while smaller, more numerous categories were not, when compared to measured ground water NO_3-N concentration data.

Soil drainage class: As NO_3-N is highly mobile with water in the soil, we incorporated into the assessment a soil factor that reflects water movement and percolation. The State Soil Geographic Data Base (STATSGO) (NRCS, 1994) contains several factors that may be used to characterize the rate of water movement through soil. STATSGO data is available for the entire state of Colorado and was selected as the best currently available, complete source of data on soil properties. Others (Navular and Engel, 1998; Fritch *et al.*, 2000a; Nolan *et al.*, 2002) have used STATSGO data in similar studies. The STATSGO database includes several classifications of soil characteristics related to permeability. However, in a similar study, Rupert (1999) determined that the soil drainage class most strongly correlated with ground water NO_3-N concentrations. Therefore, we used soil drainage in this assessment (Figure 2). Soil drainage is defined as the natural drainage condition of a soil and refers to the frequency and duration of periods when soil is free of saturation (NRCS, 1994). Soils with poor drainage are prone to chemically reducing (anaerobic) conditions that can lead to denitrification of NO_3-N. We developed the soil drainage class map by computing weighted averages of the soil drainage groups for each soil map unit polygon in the STATSGO coverage. Each of the seven STATSGO soil drainage designations was given a numerical value (Table IC) with the well-drained soils receiving higher numbers. We then averaged the numeric values for each sequence in a soil map unit polygon using the component percentage field contained in the STATSGO database, as a weighing factor. This resulted in a range of values from 0 to 6.7. We divided this range of values into

TABLE IB

Vulnerability map layers: depth to ground water index interpretation

Range of values	Description	Interpretation
1	0–6 m	High vulnerability
2	6–15 m	Medium vulnerability
3	>15 m	Low vulnerability

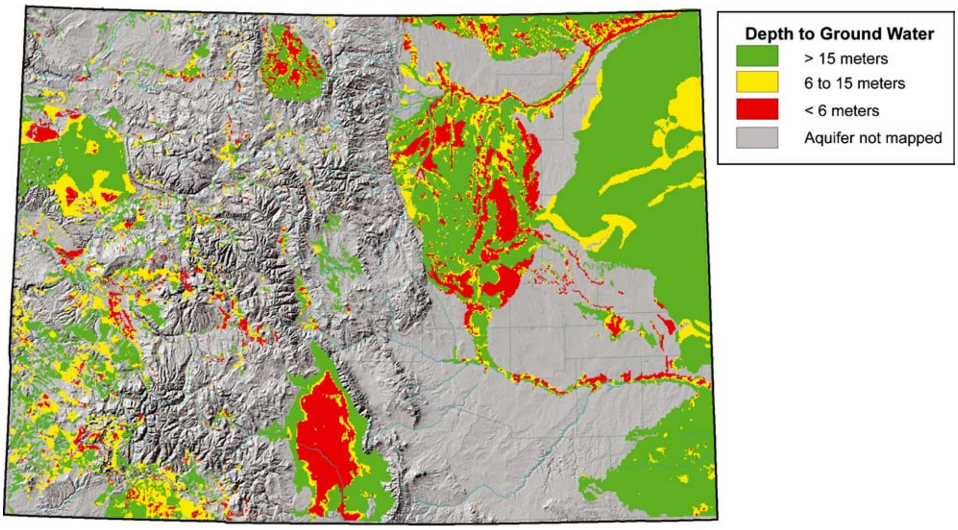

Figure 1. Depth and location of primary ground water aquifers in Colorado.

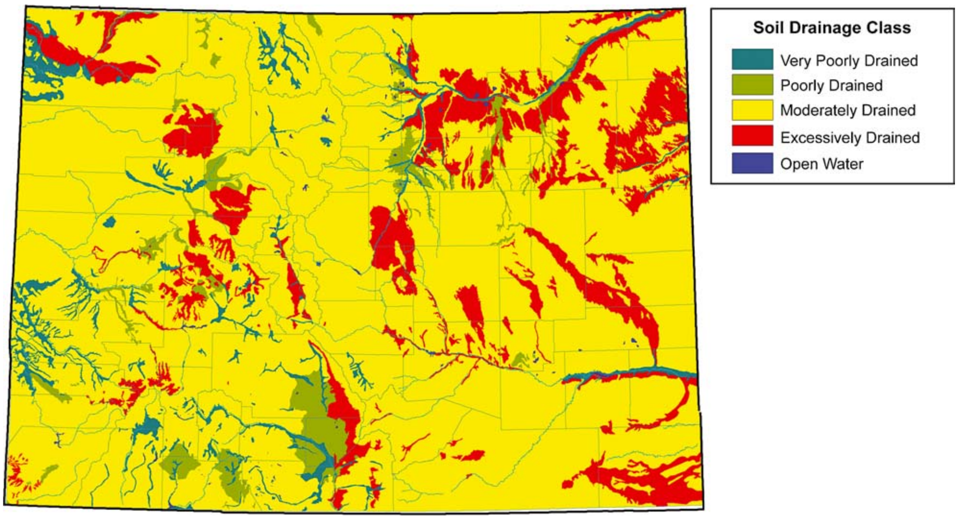

Figure 2. STATSGO soil drainage classifications for Colorado.

four general soil drainage classifications (Table ID) to combine similar weighted soil drainage averages together and to facilitate data management.

Recharge availability: Water available for ground water recharge is also an important factor for NO_3-N movement. The average annual precipitation in Colorado's agricultural areas ranges from 18 to 43 cm (Colorado Climate Center, 1984). Colorado's climate is characterized by high solar radiation, low humidity, warm temperatures, and frequent wind, resulting in evapotranspiration rates that can far exceed the precipitation received in most areas of the state. Thus, little water is naturally available for infiltration and recharge to ground water. Estimates of natural

TABLE IC
Vulnerability map layers: soil drainage designation

STATSGO designation	Interpretation	Numeric value
E	Excessive drainage	7
SE	Somewhat excessive	6
W	Well drained	5
MW	Somewhat well drained	4
SP	Somewhat poorly drained	3
P	Poorly drained	2
VP	Very poorly drained	1

TABLE ID
Vulnerability map layers: soil drainage index

Weighted average	Soil drainage category	Interpretation
5.21–6.7	4	High vulnerability
4.81–5.2	3	Medium vulnerability
3.71–4.8	2	Low vulnerability
0–3.7	1	Very low vulnerability

ground water recharge rates in Colorado are around 10 percent of precipitation or approximately 2.5–4 cm per year (Boettcher, 1966). With such little natural precipitation, irrigation is used for crop production on approximately 1.2 of the 4.45 million cropped hectares in Colorado. Irrigation greatly increases infiltration and opportunity for recharge (Klocke *et al.*, 1999; Nolan, 2000; Nolan *et al.*, 2002). Due to the increased potential for recharge under irrigated land in Colorado, we used the presence of irrigation as the best indicator of recharge availability. We used a map of Colorado's irrigated land developed by Hall (1998) from multiple sources including satellite imagery data.

Land use: Land use has been correlated with NO_3-N concentrations in ground water (Rupert, 1999). Urban and agricultural areas have been shown to contribute to NO_3-N contamination in ground water (Tesoriero and Voss, 1997) from fertilizers, manures and septic systems. We obtained the land use map from the National Land Cover Database (NLCD) in the United States Geological Survey (USGS) National Mapping Division (USGS, 2000). The USGS originally classified land uses into 21 classes; we reclassified them into four broad categories based on the associated importance of the land use to NO_3-N pollution (Aller *et al.*, 1985; Fritch *et al.*, 2000b). We rated open water and perennial ice as 0; barren soils, forested upland, herbaceous upland, and wetlands were rated as 1. It was assumed that these are largely natural areas and little NO_3-N is available to leach (Rupert, 1999). Developed land was rated a 2, as urban lands have been shown to contribute to NO_3-N contamination in ground water (Nolan *et al.*, 1997; Tesoriero and Voss, 1997). Lastly, herbaceous planted/cultivated, and non-natural woody land uses were rated

3. Cultivated lands were given a higher rating as agricultural practices have the greatest potential to contribute NO_3-N to ground water (Schepers *et al.*, 1997). We combined the irrigated land coverage described earlier with the land use coverage to compose a fourth land use class (irrigated crops) rated 4 (Table IE). The combining of these layers produced one final land use map with four different classes (Figure 3).

2.2. Vulnerability map development

Several approaches have been proposed to develop ground water vulnerability models (Focazio *et al.*, 2002). We developed and tested several equations that combine the map factors into one final map using two different methods. First, three possible equations were derived from a sensitivity analysis using the NLEAP model (Shaffer *et al.*, 1991). We used the NLEAP model as it has been successfully applied in regional scale assessments to map areas in Colorado that have high potential for NO_3-N leaching (Wylie *et al.*, 1994) and NLEAP outputs have also been used for identifying regional NO_3-N leaching distributions (Shaffer *et al.*, 1996). Factors evaluated include both management and soil physical properties. The analysis used two different soils with varying properties and 2 years of climate data from the respective NLEAP databases. Three equations were developed due to variations in the interpretation of the spatial data sources and the NLEAP analysis output (Ceplecha, 2001).

An additional equation was developed from a calibration procedure using the map factors and discrete ground water NO_3-N data points collected from throughout Colorado (Figure 4). We compared each map factor to half of the ground water data to determine which map factor was more sensitive to ground water NO_3-N concentration. We developed a map equation using this information and compared it to the remaining half of the ground water data to validate the results.

Each VM equation was compared to the statewide ground water NO_3-N concentration data shown in Figure 4. We found the best fit to be Equation (1), which was a hybrid equation derived from NLEAP factor component analysis as described

TABLE IE
Vulnerability map layers: land use and irrigation designations

Range of values	Description	Interpretation
0	Open water/ice	Not vulnerable
1	Natural/wetlands	Low vulnerability
2	Developed lands	Medium vulnerability
3	Agricultural lands	High vulnerability
4	Irrigated lands	Very high vulnerability

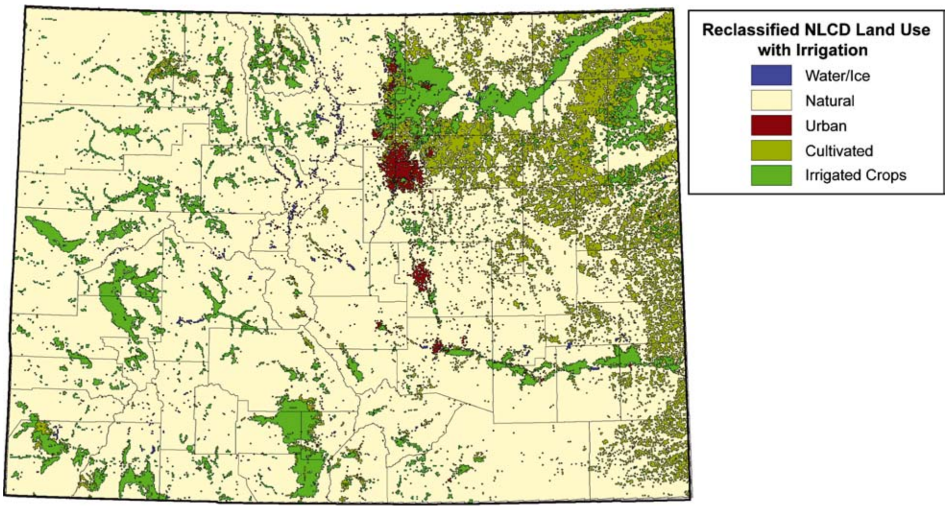

Figure 3. Reclassified National Land Cover Database (NLCD) land use in Colorado.

above.

$$\begin{aligned}&\text{Aquifer Vulnerability Value}\\&\quad=(\text{Drainage}+(\text{Land Use Index}+\text{Irrigation Index})\\&\quad+\text{Depth to Aquifer Index})*\text{Presence of Aquifer}\end{aligned}\tag{1}$$

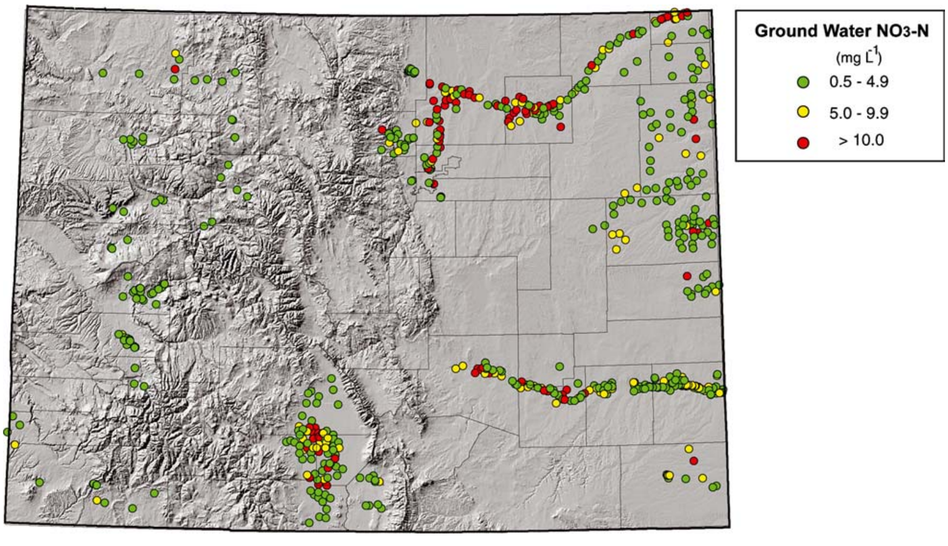

Figure 4. Colorado ground water sample points ($n = 576$) from the National Water Quality Assessment program (NAWQA) and Colorado Department of Public Health and Environment (CDPHE) monitoring events.

The other equations considered are described by Ceplecha (2001).

No units are associated with the aquifer vulnerability value, as the input map factors are qualitative. The map equation produced vulnerability index values ranging from 0 to 11, which were calculated for each polygon. The vulnerability risk was then divided into categories of high, medium, and low vulnerability and each polygon was assigned a risk rating corresponding to calculated vulnerability. The scale of the final VM (Figure 5) is limited by the input factor with the smallest map scale. The depth to ground water map has the smallest map scale (i.e. 1:500,000) thus, the final VM has a map scale of 1:500,000.

2.3. Field scale vulnerability matrix development

The VMX is a field assessment tool designed to estimate the relative potential for NO_3-N leaching to underlying aquifers as a result of field scale physical properties and management factors. Objectives for the VMX were to design a tool that accounts for important factors that influence ground water vulnerability beneath a field and is usable by farmers and their advisers. The tool was patterned after the Colorado P-Index (Sharkoff *et al.*, 2003). To keep the VMX practical, factors consisted of on-hand or readily obtainable information. A review of current literature (Ceplecha, 2001) was used to determine the parameters that most affect aquifer vulnerability on a field scale.

The VMX is designed for use on irrigated fields in Colorado. The approach assumes that there are economic limitations associated with dryland farming that prevent over-application of N fertilizer and that the dry climate in Colorado results in minimal deep percolation compared to irrigated fields. This assumption does not mean that NO_3-N movement does not occur in dryland farming areas of Colorado. Rather, it assumes that under dryland farming in semi-arid regions the amount of NO_3-N leached is negligible compared to irrigated lands (Wu *et al.*, 1997). Management of agricultural inputs such as fertilizer and irrigation water ultimately determines the extent of ground water impacts in areas of high or low sensitivity (Schepers *et al.*, 1997). The literature contains numerous reports on the importance of various factors pertaining to field scale NO_3-N leaching (Hall *et al.*, 2001; Meisinger and Delgado, 2002; Shaffer and Delgado, 2002). These studies consistently found that crop rotation, irrigation, fertilizer and manure management, and soil properties to be among the most important factors in field scale NO_3-N leaching.

To focus the user on fields with the greatest risk for NO_3-N leaching, the first component of the VMX is a screening tool to determine if the VMX should be completed for a particular field (Figure 6). The VMX consists of six factors that are evaluated and scored (Table II). Scored factors are added to obtain a final vulnerability rating. Certain best management practices (BMPs) may be credited to the final score to lower the final vulnerability. The final rating is then compared to the Nitrate VMX Interpretations (Table II). An explanation of the VMX factors, including soil texture, irrigation efficiency, total nitrogen application, manure

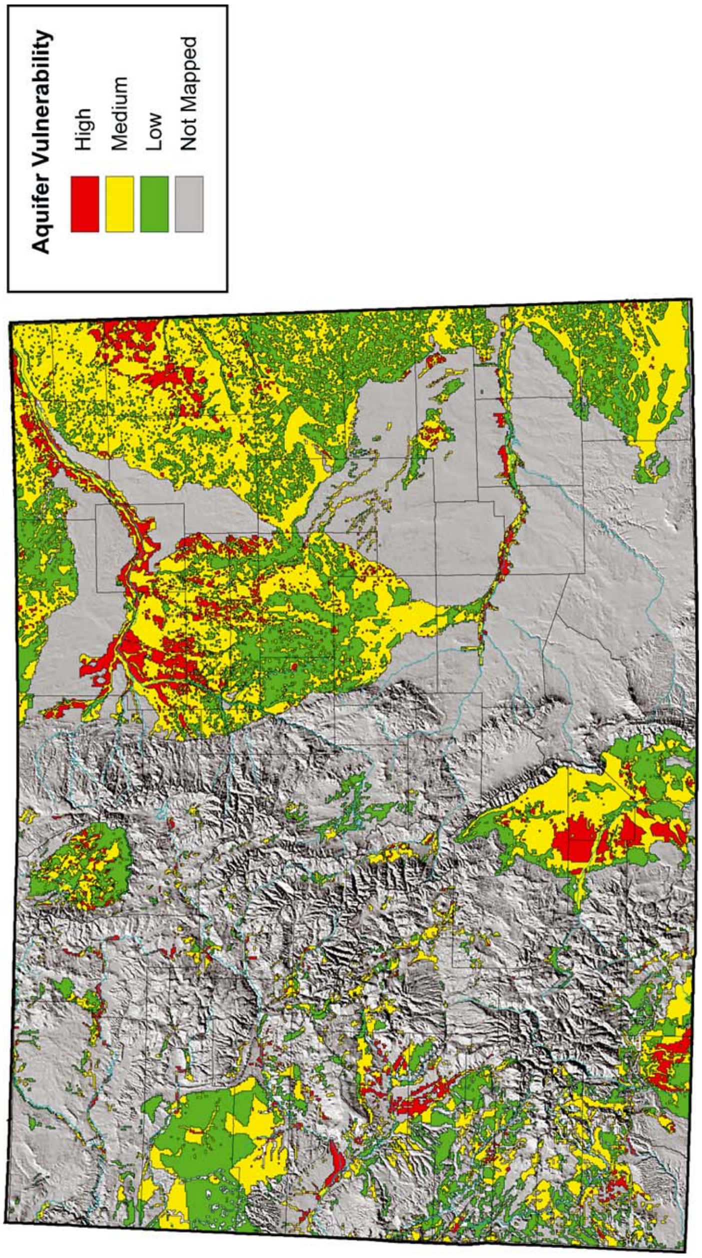

Figure 5. Colorado aquifer vulnerability to nitrate contamination.

TABLE II

Field scale vulnerability matrix: vulnerability matrix score sheet

	Factor	Vulnerability rank				Score	Nitrate leaching vulnerability matrix interpretations
a	Soil texture	1	2	3	4	< 8	This management system results in a *LOW* aquifer vulnerability to nitrate contamination. If there is an underlying aquifer that is shallow (< 6 m) or used as a drinking water source, apply the management constraints of the Medium category.
b	Irrigation efficiency	1	2	3	4	8–11	This management system results in a *MEDIUM* aquifer vulnerability to nitrate contamination. Apply N at agronomic rate or lower, using spring or split in-season applications. If there is an underlying aquifer that is shallow (< 6 m) or used as a drinking water source, apply the management constraints of the High category.
c or d	Total Nitrogen rate or manure application rate	1	2	3	4	12–15	This management system results in a *HIGH* aquifer vulnerability to nitrate contamination. Manure should be applied at P rate for the crop to be grown. Apply N using split applications during the growing season at or below the agronomic rate. Changes in irrigation management and/or method may be necessary.
e	Manure/nitrogen application timing	1	2	3	4	16	This management system results in a *VERY HIGH* aquifer vulnerability to nitrate contamination. Manure use is not recommended and appropriate BMPs should be employed.
f	BMP credits	Subtract one point if any of the listed BMPs are implemented on this field.					

application, N application timing, and BMP credits and the rating scheme for each factor is provided below and in Table II.

Soil texture: Soil properties affect the travel time and amount of water that will infiltrate into an aquifer. Properties such as soil texture, particle-size distribution, soil structure, and field capacity all affect the permeability of an area (Aulakh and Singh, 1997; Zhang *et al.*, 1998). Soil properties are field specific, and their spatial variation can be large. We chose soil texture as it is easy to obtain and understand, and spatial variability associated with soil texture is smaller than other soil properties as it reflects the uniformity of soil genesis processes (Corwin *et al.*, 1997). The VMX increases the weighting for soil texture with increasing percent sand soils due to the lower water holding capacity and higher soil permeability of sandy soils. The soil leachability classes were taken from Perry *et al.* (1988) and Kuenstler *et al.* (1994). The coarsest soil that composes greater than one-third of the field should be used to classify the entire field in the VMX (Waskom, 1994).

Irrigation efficiency: Given Colorado's semi-arid climate, fields that receive supplemental irrigation in excess of crop evapotranspiration are the most likely to cause NO_3-N leaching. Irrigation timing, amount, and method all effect NO_3-N movement through the soil and into the ground water. Many studies illustrate the influence of irrigation management on soil NO_3-N movement and the increased potential for NO_3-N leaching with decreasing irrigation efficiency (Adamsen and Rice, 1995; Martin *et al.*, 1993; Wu *et al.*, 1997). The VMX requires the user to enter

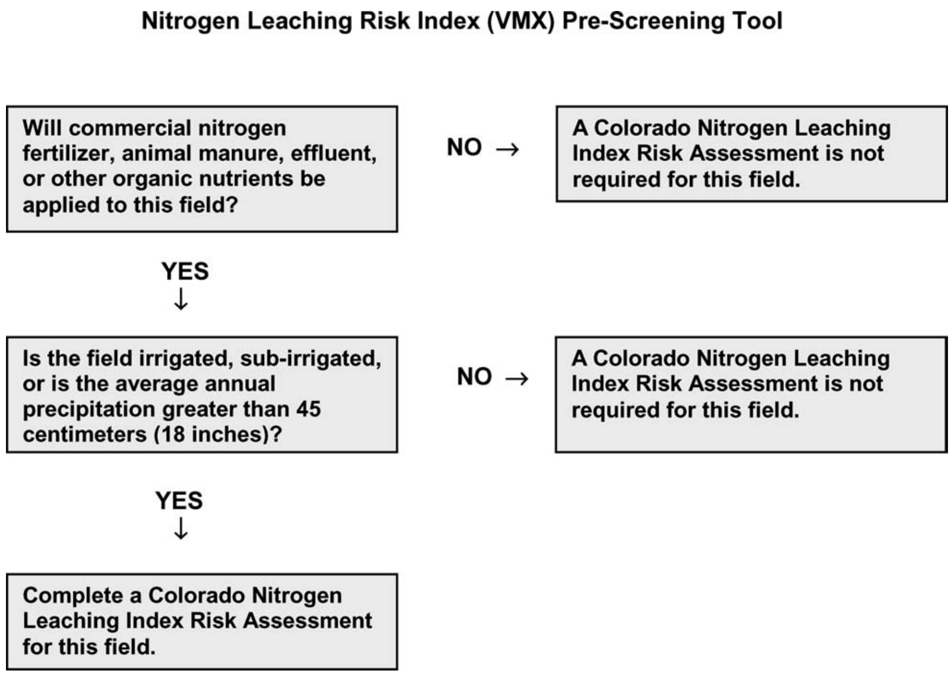

Figure 6. Nitrogen leaching risk pre-screening tool to determine need to complete the VMX.

the average irrigation application efficiency (water stored in rootzone and available for crop use/irrigation water applied, expressed as a percentage) achieved on the field (Table III; factor b). Water not consumed by crops or stored in the root zone can exit the field as runoff or deep percolation. As application efficiency decreases on finer textured soils, runoff can be higher than deep percolation due to slower infiltration. However, for this VMX we assumed decreasing application efficiency increases deep percolation, regardless of soil texture. Low application efficiency has been linked to NO_3-N leaching in Colorado (Wu *et al.*, 1997). Therefore, systems that apply water volumes greater than plant requirements increase NO_3-N leaching potential and should have a higher vulnerability rating than higher efficiency systems. The user can default to the type of irrigation system as a surrogate if the field level application efficiency has not been determined (Bauder *et al.*, 2004).

Total nitrogen application: Excess soil nitrogen not consumed by plants or immobilized by soil microbes is subject to the forces of leaching. Factors such as fertilizer type, rate, placement, and application timing can affect how much NO_3-N is available for leaching. In the VMX, the total N application factor refers to the amount of total N applied to the field for the crop year (Table III; factor c). The appropriate amount of N applied to a crop will vary depending on the crop needs, yield goal and soil conditions, so the VMX indexes the agronomic rate for the crop or crop rotation grown (Bock and Hergert, 1991). Agronomic rate is defined as the optimum nutrient application rate based upon a field-specific estimate of crop needs and an accounting of all N available to a crop prior to manure and/or fertilizer application (Waskom and Davis, 1999). Reducing N application offers the greatest potential for reducing input of NO_3-N into ground water (Zhang *et al.*, 1998). Schepers *et al.* (1997) demonstrated NO_3-N concentrations in ground water increased with increasing applications of N over the recommended or agronomic rate, particularly with applications 23 kg N ha^{-1}over the agronomic rate. If manure is the only N source used on the field, this factor is skipped and the manure/effluent application factor (Table III; factor d) is used in calculating the final vulnerability rating.

Manure/effluent application: Manure use has been shown to be a large contributor to NO_3-N leaching in Colorado (Hall *et al.*, 2001). Not accounted for, this N source can lead to increased soil NO_3-N levels that are subject to leaching (Power *et al.*, 2000). Eltun (1995) concluded manure management plays an important role in how much NO_3-N is available for leaching. The manure application rating is based on the amount of manure N applied to a field (Table III; factor d). It is used in place of the total nitrogen application factor if manure is the sole N source for the field. Manure application rates are typically based on N or phosphorus (P), depending on soil test levels and crop need. Manure applied to meet crop P need typically results in a lower application rate than manure applied to meet crop N need, for non-legume crops. Hall *et al.* (2001) and Power *et al.* (2000) have shown that manure applied in consecutive years can have a large cumulative impact on the amount of NO_3-N leached to ground water.

Nitrogen application timing: Nitrogen applied closer to the time of crop uptake has less potential for loss (Kuenstler *et al.*, 1994). Thus, N applied during the spring and split during the growing season has less potential for movement than fall or winter applied N. Many studies (Power *et al.*, 2000; Seeling, 2000) show application timing to be an important factor in NO_3-N leaching. Thus, N application timing in the VMX is scored depending upon when N is applied in relation to crop uptake (Table III; factor e).

BMP credits: Specific BMPs may be implemented to decrease the overall NO_3-N leaching vulnerability score (Table III; factor f). One point is subtracted from the total vulnerability score for each of the listed BMPs used on the field.

TABLE III

Field scale vulnerability matrix factors

	Soil texture			
Factor a	Class 1	Class 2	Class 3	Class 4
	Sandy clay loam or finer	Fine sandy loam to silt loam	Sandy loam to loamy fine sand	Loamy sand or coarser
Vulnerability rating	1	2	3	4
	Irrigation efficiency			
Factor b	High efficiency	Moderate efficiency	Moderately-low efficiency	Low efficiency
	>85% efficient	60% – 85% efficient	35% – 60% efficient	<35% efficient
	Microirrigation, drip low pressure center pivots, LEPA	High pressure center pivots, Side roll/hand move, Furrow with surge	Border irrigation, Furrow no cutback	Flood irrigation
Vulnerability rating	1	2	3	4
	Total nitrogen application (N fertilizer and manure)			
Factor c	Low vulnerability application	Moderately-low vulnerability application	Moderate vulnerability application	High vulnerability application
	Total N application below agronomic rate	Total N application equal to agronomic rate	Total N application 1 to 23 kg/ha above agronomic rate	Total N application in excess of 23 kg/ha above agronomic rate
Vulnerability rating	1	2	3	4

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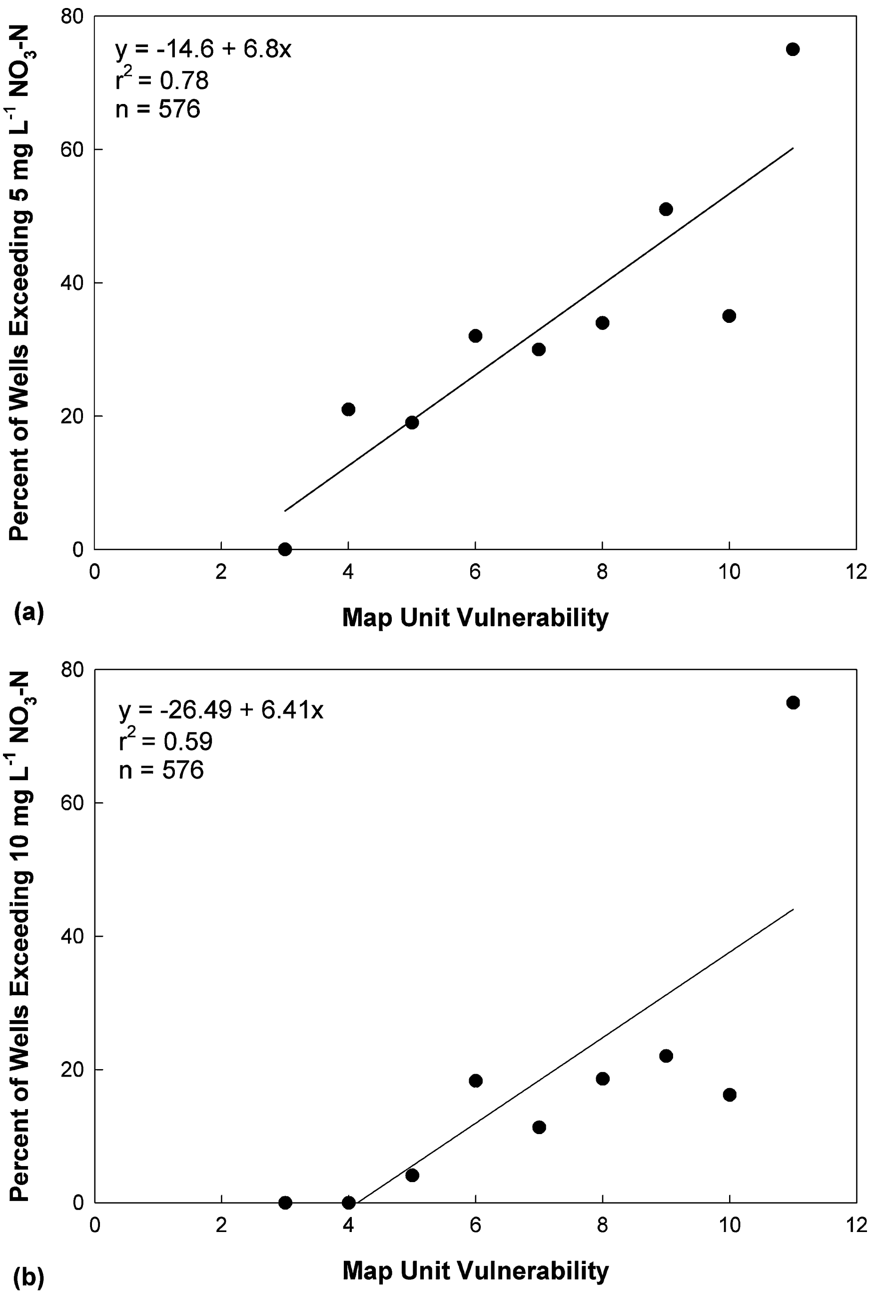

Figure 7. Percent of wells with NO_3-N concentration >5 mg L^{-1} (a) and >10 mg L^{-1} (b) at a given map vulnerability rating.

TABLE III
(Continued.)

Factor d	Manure/effluent application only: Low vulnerability application	Moderately-low vulnerability application	Moderate vulner-ability application	High vulner-ability application
	Applied at P agronomic rate	Applied at N agronomic rate	Applied above N agronomic rate (1–23kg/ha)	Applied above N agronomic rate (1–23kg/ha) for more than one consecutive year or single application > 23 kg/ha above agronomic rate
Vulnerability rating	1	2	3	4

Factor e	Nitrogen application timing: Low risk application	Moderately-low risk application	Moderate risk application	High risk application
	In-season split N application (2 or more splits)	N application 1–3 months before crop planting	N application 3–5 months before crop planting	N application > 5 months before crop planting
Vulnerability rating	1	2	3	4

Factor f	Best management practice
	(1) Slow release commercial N fertilizer.
	(2) Nitrification inhibitor use.
	(3) Use of fall planted winter cover crop, such as winter wheat or rye.
	(4) Use of a deep rooted crop, such as alfalfa, in rotation.
	(5) Sub-soil nitrogen credit from deep (122 cm) soil sampling.

Depth to ground water is not included in the VMX as the goal of the VMX is to encourage efficient N and water use, and reduce NO_3-N that could be subject to leaching. The more NO_3-N available for leaching increases the probability of aquifer contamination. Once NO_3-N is past the root zone it is largely a matter of time before it reaches the aquifer (Lampman, 1995). Nitrate below the root zone can be converted into atmospheric N via denitrification, but this loss is usually minimal (Jacinthe *et al.*, 1998). Including depth to aquifer in the VMX would lower incentive for farms overlaying deep aquifers to change management practices to reduce excess NO_3-N. If the depth to aquifer is 6 m or less, or the aquifer is used as a drinking water source, the VMX suggests additional precautions should be taken to reduce excess soil NO_3-N.

3. Results and Discussion

3.1. Vulnerability map validation

A range of output values was produced by the VM map equation. Output from the map equation for a given polygon was regressed against ground water NO_3-N concentration measured within that polygon. There were significant ($P < 0.05$) increases in observed NO_3-N concentrations with increasing vulnerability, but the relationships were poorly explained by linear regression models ($r^2 = 0.020 - 0.016$). This result was anticipated, as site-specific variables not identified in map input layers such as feedlots, soil variability and point sources of NO_3-N pollution can influence individual ground water NO_3-N concentrations found in wells at a single point within a polygon. The VM cannot compensate for site-specific variables, nor is it expected to correlate directly with measured ground water NO_3-N concentrations. However, the map should be able to distinguish areas with multiple wells that have elevated levels of contamination. We found a significant relationship existed between the map equation output and the percent of all wells exceeding 5 and 10 mg L−1 NO_3-N ($P < 0.001$ and 0.01, respectively). Mapping unit vulnerability explained the percent of wells with >5 mg L^{-1} NO_3-N (Figure 7A) and >10 mg L^{-1}(Figure 7B) with $r^2 = 0.78$ and 0.59, respectively.

The relationship between the categorized vulnerability of the associated map unit and the percent of wells with ground water NO_3-N concentrations between 0–5, 5–10 and >10 mg L^{-1} NO_3-N was examined (Figure 8). These NO_3-N levels

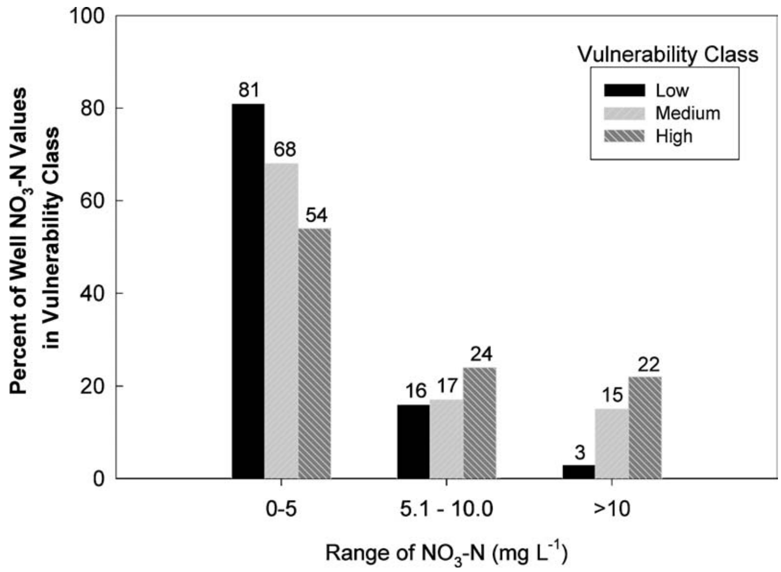

Figure 8. Percent of wells with NO_3-N levels from 0–5, 5.1–10, and > 10 mg L^{-1} in each map vulnerability class.

were selected because the U.S. Environmental Protection Agency maximum contaminant level (MCL) for drinking water is 10 mg L^{-1} NO_3-N and 5 mg L^{-1} NO_3-N was previously reported to represent impacts from human activity (Rupert, 2002). If the map is valid, a greater fraction of wells that fall into the "high" vulnerability class should have increased NO_3-N levels. Conversely, as vulnerability class decreases, there should be fewer wells with elevated NO_3-N levels. Of the 576 ground water sample points used for the validation, 15.6% were located in the "low" areas, and 50.3% and 34.3% were located in the medium and high classifications, respectively. Figure 8 shows that about 22% of the wells that fell in the "high" vulnerability class had a ground water NO_3-N concentration of 10 mg L^{-1} or higher. Only 3% of the wells that fell into the "low" vulnerability class had an NO_3-N concentration at or above 10 mg L^{-1}. About 15% of the wells that fell into the "medium" vulnerability class had an NO_3-N concentration at or above 10 mg L^{-1}. The final VM (Figure 5) divides Colorado into areas of "high", "medium", and "low" vulnerability. The "low" class areas consist of about 36% of the total area classified by the map, the "medium" class consists of 54%, and the "high" class consists of about 10% of the total area. With only 22% of the wells in the "high" areas exceeding 10 mg L^{-1} NO_3-N, it might suggest that the map overestimates ground water NO_3-N vulnerability. However, the VM only predicts the leaching potential under mapped aquifer characteristics and land use. Actual land uses, management, and N inputs in these areas will determine the extent and severity of NO_3-N contamination.

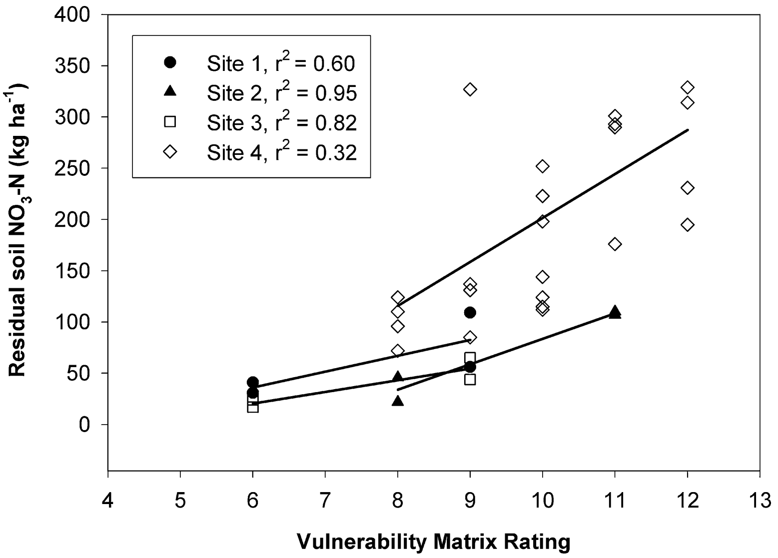

Figure 9. Relationship between residual soil NO_3-N in the 0–122 cm profile and field vulnerability (VMX) rating from four field sites.

3.2. Vulnerability matrix validation

We evaluated the VMX using data from four different field sites (Crookston and Hoffner, 1995, 1996; Spellman, 1999). Criteria for validation data included: post-season soil NO_3-N concentrations to 122 cm, N and manure management information, soil texture, and irrigation type. We ran the data for each field site through the VMX and compared the output to post-season soil NO_3-N concentrations in the top 122 cm of soil. Since the studies used did not measure N leached, only residual soil N, we assumed soil NO_3-N remaining in the top 122 cm could be used as an indicator of N available for leaching. Ground water NO_3-N concentrations were not used in the validation process, as the VMX does not account for time associated with NO_3-N movement into the underlying aquifer. Also, NO_3-N found in ground water under a field could come from other sources, depending on ground water flow direction, influence from wells or management practices. It should be emphasized that the projects from which the validation data were taken were not specifically designed to test the VMX.

Results of this validation demonstrated that residual soil NO_3-N concentrations were related to the VMX output ($r^2 = 0.95 - 0.32$) (Figure 9). VMX ratings for these sites increased with increasing residual soil NO_3-N, indicating an increased risk of N loss from the field. This validation suggests that the VMX is able to separate field-scale aquifer vulnerability. However, a more rigorous validation of the VMX is needed to provide certainty that it accurately predicts field scale leaching risk in the geographic region of interest.

4. Summary and Conclusions

In response to concern about ground water quality, two qualitative methods were developed to assess the vulnerability of Colorado aquifers to NO_3-N contamination. The aquifer VM and the field VMX allows users to evaluate aquifer vulnerability to NO_3-N leaching on a regional and field scale. The VM can identify general areas where increased vulnerability may merit additional scrutiny or protection. In areas identified as having a relatively higher risk of NO_3-N contamination than others, use of the VMX may help producers determine risk and best practices on individual fields.

In a comparison of actual ground water NO_3-N concentrations to predicted vulnerability, we found the VM was able to delineate general areas of increased aquifer vulnerability to NO_3-N contamination in Colorado. Comparison of statewide ground water NO_3-N concentrations to the aquifer VM suggested the VM is based on sound principles and is able to delineate vulnerable and non-vulnerable areas. This method is an improvement over previous aquifer assessments because it combines all relevant spatial information pertaining to aquifer vulnerability that is currently available in digital format for use in Colorado and it was validated using actual ground water data from throughout the state.

A matrix was also developed to index aquifer vulnerability on a field scale. We applied the VMX to three sources of field data to establish if the VMX could determine relative vulnerability for the different fields. The VMX outputs were correlated with residual soil NO_3-N concentrations in the top 122 cm of soil, showing increasing VMX index values with increasing residual soil NO_3-N concentrations. The processes used to develop the Colorado nitrate VM and VMX could be cost effectively applied to other geographical locations, especially those in semi-arid areas where irrigation is common.

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