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Identifying regional groundwater risk areas using a WWW GIS model system

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Abstract: To evaluate the National Agricultural Pesticide Risk Analysis (NAPRA) WWW system (http://pasture.ecn.purdue.edu/~napra), NAPRA WWW predicted nitrate and atrazine losses to shallow groundwater were compared with well nitrate and atrazine data within Indiana. The NAPRA system correctly categorised 84% of the 'High' and 'Very High' nitrate observations, although the predicted nitrate losses are generally in more severe categories than measured nitrate levels. The NAPRA system also correctly categorised 69% of the 'High' and 'Very High' atrazine observations. Predicted results match measured concentrations reasonably, if assumptions and limitations of the NAPRA WWW system are considered. This system has the potential to identify areas vulnerable to nitrate and atrazine groundwater pollution. Thus, a web GIS version of the NAPRA model was developed (http://pasture.ecn.purdue.edu/~napra/NAPRA_SPATIAL) to facilitate the assessment of the effects of more refined agricultural management on water quality at farm field scales.

Keywords: GLEAMS; groundwater; NAPRA WWW; nutrient; pesticide; risk analysis; Web GIS.

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Zhenxu Tang has a PhD in agricultural and biological engineering from Purdue University. She is developing web-based decision support systems to evaluate soil erosion/sediment/water quality/urban sprawl related concerns.

1 Introduction

Groundwater is an important resource in much of the Midwest USA with more than 95% of residents in rural areas and more than 50% of urban residents using groundwater as their primary source of drinking water (US Geological Survey, 1995). Major aquifer systems in Indiana provide drinking water for over 60% of the state's population and around 90% of the people in rural areas (IDEM, 1989). Thus, protecting groundwater in the Midwest USA is of great significance (US EPA, 1992). Regional risk to nonpoint source (NPS) contamination maps can be used to create efficient groundwater management and protection plans. However, nitrate and pesticide movements to groundwater are not uniform because of variable management, soils, underlying geologic materials, and climate conditions. Soil, climate, and agronomic practices are the primary factors affecting groundwater vulnerability to pesticide contamination (Burkart et al., 1999). As the nature of agricultural NPS pollution is essentially spatial, it is appropriate to use a spatial analysis system to analyse and model the data related to the problem. Thus, the web-based NAPRA system has been developed to estimate the site specific effects of land use and management on water quality with respect to the risk of nutrient and pesticide pollution of groundwater.

The objectives of this investigation were:

- To evaluate the nutrient enabled National Agricultural Pesticide Risk Analysis (NAPRA) WWW system by comparing predicted nitrate and atrazine (a common herbicide) losses to shallow groundwater with measured well water quality data.
- To develop a Web GIS version of the NAPRA system to allow assessment of the effects of agricultural management systems on water quality at a farm field scale.

2 Literature review

Excessive levels of nitrate or nitrite, concentrations of nitrate which exceed 10 milligrams per litre (ppm) or nitrite which exceeds 1 milligram per litre, in drinking water can be lethal to infants under six months of age (US EPA, 1992). Pesticides have been found in groundwater across the nation (Cohen et al., 1986), and pesticide concentrations are higher than federal and state specified health standards in many cases (US EPA, 1992). Nonpoint sources are often responsible for nitrate and pesticides in groundwater. However, it is difficult to predict NPS pollution in groundwater due to agricultural activities because numerous factors including soil, climate, crop, rate and timing of pesticide and nutrient applications and tillage affect the movement of NPS pollutants.

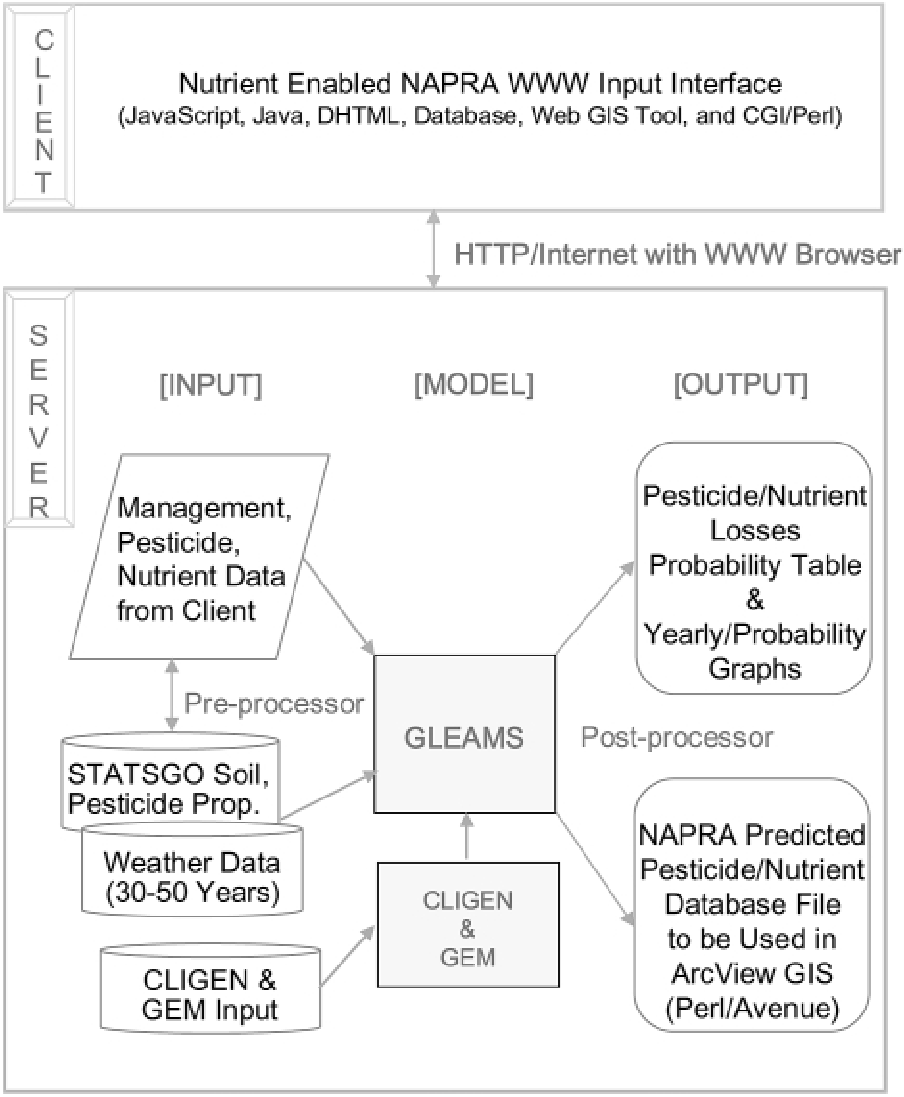
To estimate groundwater vulnerability to agricultural NPS pollution in Indiana, DRASTIC, System for Early Evaluation of Pollution potential of Agricultural Groundwater Environments (SEEPAGE), and Soil Pesticide Interaction Screening Procedure (SPISP) have been used (Engel et al., 1996). DRASTIC considers various hydrogeological settings that influence the pollution potential of a region (Aller et al., 1987). The SEEPAGE considers various hydrogeological settings and physical properties of the soil that affect the groundwater vulnerability to pollution potential (Moore, 1990). SPISP considers pesticide properties and soil properties in predicting the vulnerability of water (Goss and Wauchope, 1992). The DRASTIC, SEEPAGE, and SPISP approaches for predicting groundwater vulnerability performed reasonably well for both nutrients and pesticides within Indiana (Engel et al., 1996). The maps resulting from these indices have been used to target groundwater protection efforts within Indiana (Engel et al., 1996). Navulur and Engel (1997) developed a new technique to estimate groundwater pollution potential from nonpoint nitrate pollution. Their technique is a modification of the DRASTIC model and uses an additional data layer, estimated nitrate leached (NL), along with the hydrogeologic settings: aquifer recharge, slope, soil media, aquifer media, and vadose zone. Their technique performed better than the conventional DRASTIC and SEEPAGE analyses (Navulur and Engel, 1997). However, these approaches do not consider the effects of site-specific agricultural management in estimating the nutrient and pesticide vulnerability of surface water and shallow groundwater.

A decision support system that can assess the effects on water quality of site-specific agricultural management systems, soil properties, land use, and weather is needed for developing better pesticide and nutrient management plans. Thus, the NAPRA WWW system was developed (http://pasture.ecn.purdue.eud/~napra) to simulate the effects of agricultural management systems on pesticide water quality (Engel and Lee, 1998; Manguerra et al., 1997). The NAPRA users describe agronomic and pesticide management, such as pesticide application date, method, and amount, along with the geographic location of interest. The NAPRA system has been extended to consider nutrient losses and other NAPRA features have been enhanced (Lim and Engel, 1998, 1999, 2000, 2003).

There are two versions of the NAPRA WWW system. The single field version can be used for a single soil, while the county version can be used for multiple soils within a county or area. The NAPRA WWW system builds the input parameter files for the Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) (Knisel and Davis, 1999) model from user provided crop management, pesticide, and nutrient data in the input interface, by querying databases and by running weather generator models (Figure 1). The NAPRA postprocessor computes pesticide and nutrient loss probability of exceedance and historic loss curves. The same processes of the single field version of the NAPRA WWW system are iterated for soils within a county or area in the county version of the NAPRA WWW system. Perl and ArcView Avenue scripts were written to automate the processes of providing NAPRA predicted results in a desktop GIS map format (Lim and Engel, 2003). The NAPRA WWW system provides easy-to-access and easy-to-use decision support capabilities to decision makers, and it can be used to develop pesticide and nutrient management plans to minimise the risk of pesticide and nutrient pollution. The NAPRA users only need a web browser and internet access to utilise this web-based system since all computational tasks are performed on the server.

Although programmes were written to automate the processes of mapping the NAPRA results in a desktop GIS map format, this restricts its use to experienced GIS users and those with desktop GIS software. Thus, it would be desirable to deliver NAPRA maps within the user's web browser.

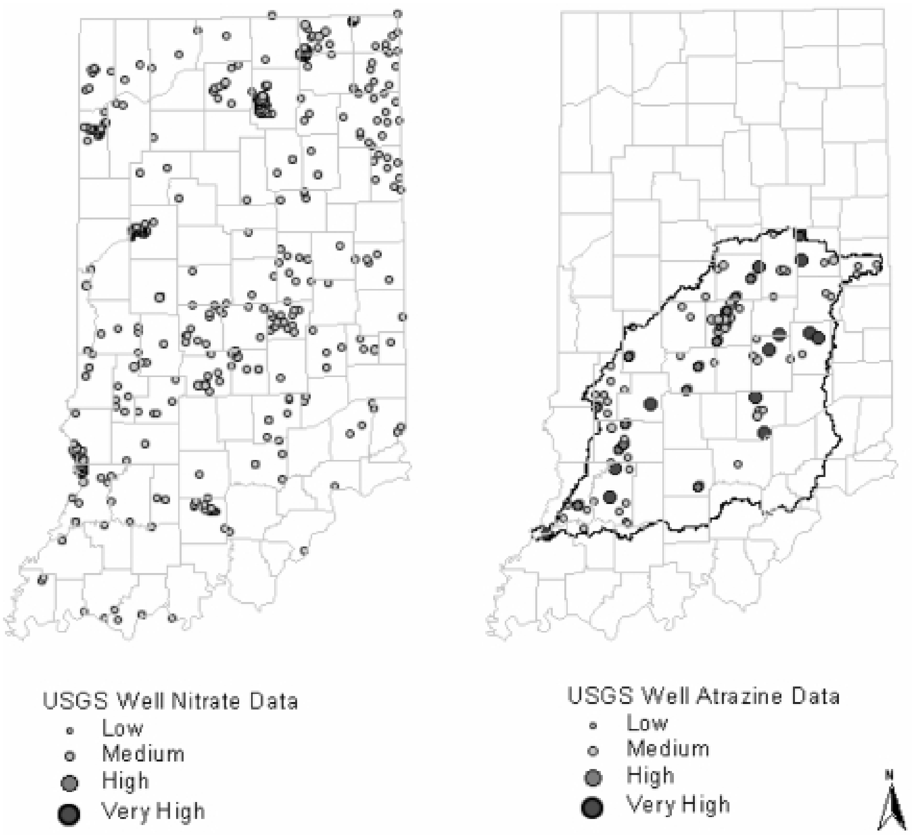
Figure 1 Overview of the NAPRA WWW System (Lim and Engel, 2003)



3 Methodology

Nitrate and atrazine losses were simulated and compared with USGS well water quality data within Indiana to evaluate the predictive ability of the NAPRA WWW system. The USGS well nitrate and atrazine sampling locations are shown in Figure 2. Well samples from these locations were analysed by USGS. The size of the point for each well indicates the level of nitrate and atrazine detected at that sampling location. The well nitrate and atrazine data were classified into four groups using the natural break classification method: Low, Medium, High, and Very High. These classes were compared with the NAPRA predicted data that was also grouped into qualitative categories, because groundwater quality is not affected only by the nearby areas, but by larger surrounding areas. Thus, relative comparisons are more appropriate than a direct comparison.

Figure 2 USGS well nitrate and atrazine sampling locations in Indiana



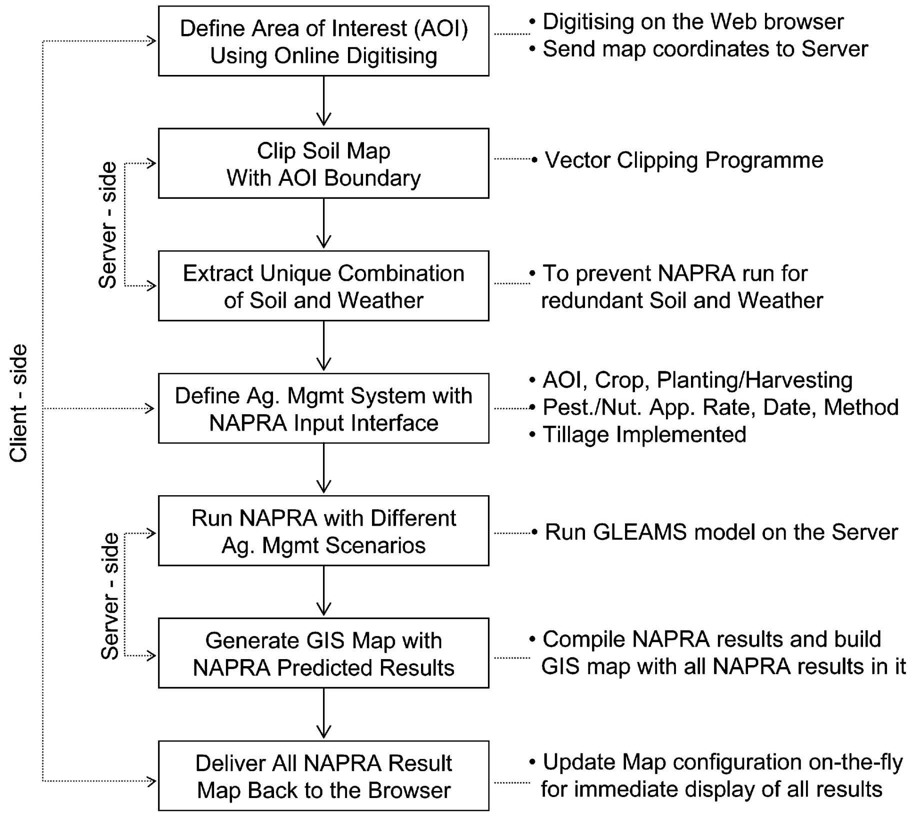
The NAPRA WWW system was run with state average nutrient and atrazine application rates for continuous corn. To run NAPRA for all of Indiana, the combinations of state soil geographic database (STATSGO) (NRCS, 1992) soils and Thiessen weather polygons were prepared with a GIS. There are up to 21 components for each Map Unit ID (MUID) in STATSGO soil data. Thus, the average NAPRA WWW predicted values for each combination of STATSGO soil and the Thiessen weather polygon were obtained by averaging the predicted values based on the relative percentage of areas of each component in a MUID.

The NAPRA WWW system simulates the movements of atrazine and nitrate below the root zone, and it can be assumed that much of the atrazine and nitrate leached below the root zone is lost to shallow groundwater if subsurface drainage systems are not present. Some leached atrazine and nutrients may move to surface water through subsurface drainage systems and therefore, not reach groundwater. Thus, subsurface drainage system area by county data were obtained from the US Census of Agriculture (1974) to account for this. Atrazine and nitrate loadings to groundwater were computed by subtracting the estimated portion that moves to surface water through subsurface drainage systems from the NAPRA WWW predicted atrazine and nitrate leached below the root zone.

The NAPRA WWW predicted nitrate and atrazine values in shallow groundwater were computed and were linked to the GIS map. The NAPRA WWW predicted nitrate and atrazine maps were resampled using the cubic convolution method (ESRI, 2000). The cubic convolution method uses the values of 16 pixels in a 4×4 window to calculate an output value. In cubic convolution, the pixels farthest from the output pixel in the 4×4 window have less weight than those close to the output pixel. Since a cubic, rather than a linear, function is used to weight the 16 input pixels, the pixels farther from the desired location have exponentially less weight than those closer to it. Typically, the mean and standard deviation of the output pixels closely match those of the input pixels when using cubic convolution (ESRI, 2000). The resulting maps were used for nitrate and atrazine comparisons with the USGS well data in this study.

Although the county version of NAPRA WWW system provides an easy to use interface for the simulation of various agricultural management systems on water quality, it requires experience and a significant effort to compile predicted results and to reformat them for linkage to maps on a desktop GIS. Thus, a fully integrated and automated web GIS version of the NAPRA system was developed in this study using Java, JavaScript, and Perl CGI programmes, and the Mapserver CGI application (Mapserver). The Java applet that comes with the Mapserver CGI application was customised, and an online digitising function was added to the applet to allow users to define the area of interest (AOI) within a web browser using the mouse. A vector clipping programme was written to clip the soil map with the user defined AOI. The preprocessor retrieves the unique combinations of soil mapping units and weather. Users can then define agricultural management systems, such as cropping, planting, harvesting, pesticide and nutrient application rates, dates, and methods, and tillage for these areas. The core model of the NAPRA WWW system, GLEAMS (Knisel and Davis, 1999), is run with user defined agricultural management systems for each unique combination of soil and weather. The post-processor creates a GIS map, in ArcView Shapefile format, with the NAPRA predicted pesticide and nutrient results. The NAPRA predicted results are displayed in the GIS map in the web browser, thus users can visualise the spatial variation of the predicted pesticide and nutrient losses. An overview of the web GIS version of the NAPRA Spatial Decision Support System is provided in Figure 3. The procedures depicted in Figure 3 are fully integrated and automated, thus users can easily assess the impacts of various agricultural management systems on agricultural NPS pollution.

Figure 3 Overview of the web GIS version of the NAPRA WWW system



4 Results and discussion

4.1 Comparison of NAPRA predicted nitrate and atrazine data with USGS well water quality data

The predicted nitrate values in northern Indiana are generally higher than those of central Indiana (Figure 4), and these generally match the measured nitrate data in shallow groundwater as shown in Figure 2. The comparison of NAPRA WWW predicted nitrate leached to shallow groundwater with the measured USGS well nitrate data is shown in Table 1. NPARA WWW correctly categorized 84% of the High and Very High nitrate observations, even though NAPRA WWW estimated High and Very High potential for nitrate loss to groundwater for only 45% of the state. Based on the results shown in Table 1, NAPRA WWW has the potential to identify areas within Indiana that are vulnerable to NPS nitrate reaching groundwater.

Figure 4 NAPRA WWW predicted nitrate losses to shallow groundwater

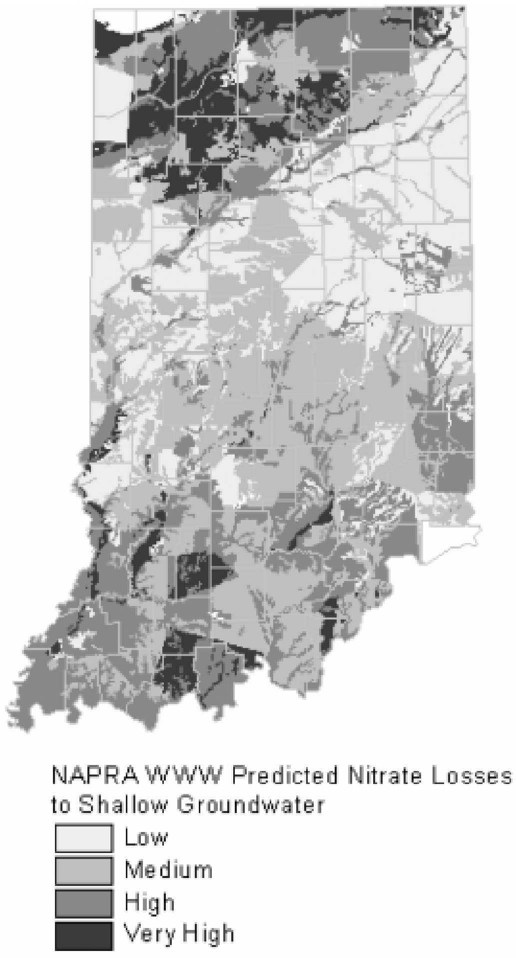


Table 1 Comparison of NAPRA WWW predicted nitrate leached to shallow groundwater with measured USGS nitrate concentration data in wells

Measured nitrate in wells	*NAPRA predicted nitrate leached*			
	Low	*Moderate*	*High*	*Very high*
Low	93	98	139	50
Moderate	10	27	54	15
High	10	20	40	5
Very high	6	2	128	34

Note: The values used in this table represent the number of wells in each category.

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The NAPRA WWW predicted atrazine losses below the root zone are shown in Figure 5. The predicted atrazine values are generally higher where the higher concentrations of atrazine were detected in the White River Basin. The comparison of NAPRA WWW predicted atrazine losses below the root zone with measured atrazine detections in wells is shown in Table 2. NAPRA WWW correctly categorised 69% of the High and Very High observations, while NAPRA WWW estimated High and Very High potential for atrazine loss to groundwater in 24% of the area of the White River Basin. Note that a potential in the High or Very High categories as predicted by NAPRA WWW does not mean that the measured concentration will be High or Very High, rather it indicates the potential for greater losses of atrazine in these areas. Based on the results in Table 2, the NAPRA WWWW has the potential to identify areas within the White River Basin that are vulnerable to atrazine below the root zone.

Figure 5 NAPRA WWW predicted atrazine losses to shallow groundwater

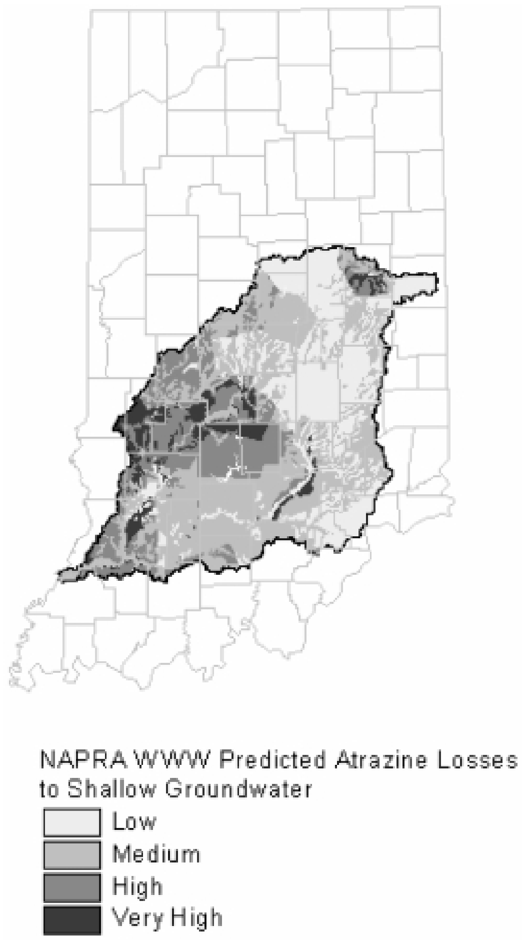


Table 2 Comparison of the NAPRA WWW predicted atrazine leached to shallow groundwater with measured atrazine concentrations data in wells

Measured atrazine in wells	*NAPRA predicted atrazine leached*			
	Low	*Medium*	*High*	*Very high*
Low	20	16	21	12
Medium	4	3	1	1
High	1	1	5	1
Very high	2	1	3	2

Note: The values used in this table represent the number of wells in each category.

The NAPRA WWW estimates of nitrate and atrazine losses are generally in more severe categories than observed levels. This is expected and can be explained as follows. The NAPRA WWW predicted results indicate there is a *potential* for NPS loss in that region. The NAPRA WWW predicts nitrate and atrazine movement below the root zone, but this does not guarantee that they will reach wells. The NAPRA predicted nitrate and atrazine values were computed based on water and pollutant masses moving below the root zone. Groundwater is often recharged from large areas with water that may contain lower pollutant levels. The effects of groundwater recharge were not considered in this study due to the complexity of groundwater recharge. This is probably one of the reasons why the NAPRA WWW predicted nitrate and atrazine values are higher.

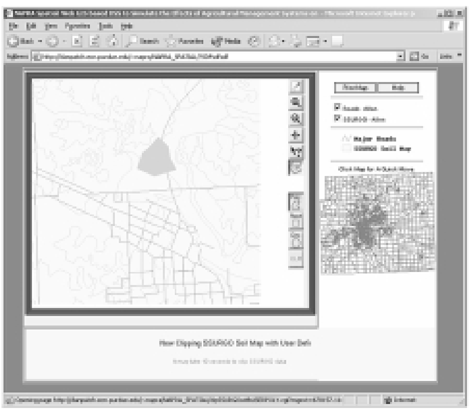
In NAPRA runs, it was assumed that root zone depth is fixed (76.2 cm), except when the depth to the bottom of the soil layer is lower than the root zone depth. Previous results indicated that predicted nitrogen and atrazine in runoff is not highly sensitive to the root zone depth, but predicted losses below the root zone are very sensitive to the root zone depth (Knisel and Davis, 1999). These results indicate the importance of the definition of the root zone depth, and inaccuracies in defining the root zone depth could account for some of the differences between predicted and observed nitrate.

There were few observations (16%) of High and Very High nitrate concentrations when NAPRA predicted Low or Moderate potential for nitrate leached to shallow groundwater. The USGS measured nitrate concentration data were generally collected in regions with potential concern about groundwater quality, and thus likely contain higher concentrations of nitrate than would random samples. Point sources of nitrates and incorrect estimation of drainage percentage may also be responsible for some of the improperly predicted nitrate detections. In this study, hydrogeologic settings, such as underlying aquifer properties, groundwater recharge areas, and depth to water table, were not considered. Therefore, further studies need to be completed to identify the effects of hydrogeologic settings and nutrient discharges from septic systems or point sources on groundwater quality.

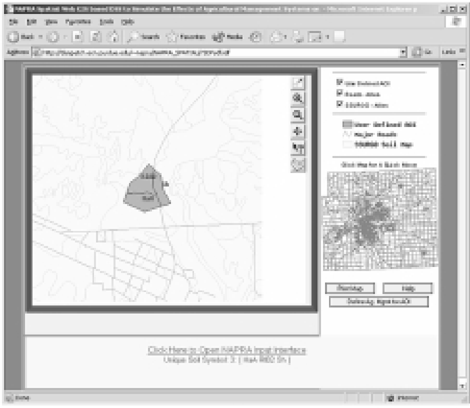
4.2 Development of the web GIS version of NAPRA DSS

The web GIS version of the NAPRA system is available at http://pasture.ecn.purdue.edu/~napra/NAPRA_SPATIAL. The fully integrated and automated web GIS version of the NAPRA system is shown in Figure 6. Users can define the region of interest with an online digitising function developed in this study (Figure 6 (a)). The

Figure 6 Web GIS version of the NAPRA spatial decision support system

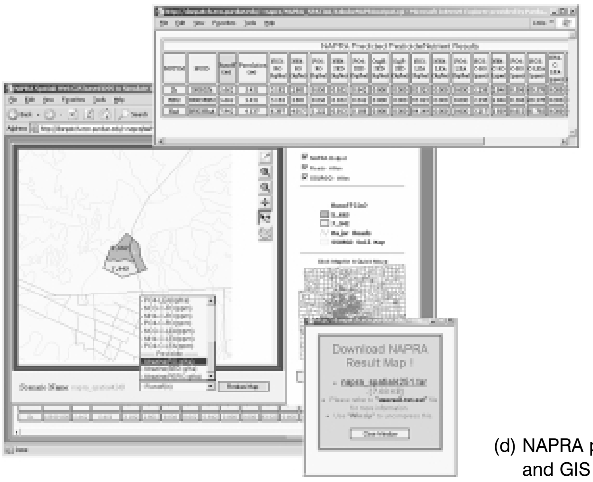


(a) Online digitising and clipping



(b) Identify unique soils

(c) Agricultural management for AOI



(d) NAPRA predicted tabular and GIS results newly developed vector clipping programme clips the soil map with the user defined area of interest (AOI). A series of NAPRA runs is prepared for the unique soils within the AOI (Figure 6 (b)). Users define the agricultural management systems to be applied (Figure 6 (c)). The NAPRA predicted results are delivered back to the user's web browser. Users can then create more than 20 NAPRA predicted pesticide and nutrient loss maps with simple pulldown menus. Users can also download the NAPRA predicted results in desktop GIS map formats for further analysis or reporting purposes (Figure 6 (d)). As shown in Figure 6, users can see the spatial variations of the NAPRA predicted results due to different agricultural management systems and soil types with the fully integrated and automated NAPRA.

5 Conclusions

The NAPRA WWW system was run for Indiana using state average nutrient and atrazine application rates for corn to evaluate the predictive ability of the NAPRA WWW system. The NAPRA system predicted nitrate concentration values were compared with nitrate well water quality data. The NAPRA system correctly categorised 84% of the High and Very High nitrate observations, although the predicted nitrate losses are generally in more severe categories than measured nitrate levels. The NAPRA system also correctly categorised 69% of the High and Very High atrazine observations. The NAPRA estimates of nitrate and atrazine losses are generally in more severe categories compared to measured levels. This is expected since the NAPRA WWW predicted results indicate there is a *potential* for NPS pollution loss, and these are the amounts of estimated nitrate and atrazine movement below the root zone, and not necessarily to the groundwater reaching the sampled wells. The NAPRA WWW predicted results match measured nitrate and atrazine concentrations reasonably well, if assumptions and limitations of the NAPRA WWW system are considered. This system has the potential to identify areas where groundwater is vulnerable to nitrate and atrazine NPS pollution.

The web GIS version of the NAPRA system is an ideal tool to assess the effects on water quality of site-specific agricultural management systems at the field scale level. Contrary to the previous county version of the NAPRA WWW system, all processes are fully integrated and automated. Thus, users can easily examine the spatial variation in the predicted water quality results with a web browser and internet access. Although this web GIS version of the system provides an easy-to-use and easy-to-access system, it has some drawbacks, such as:

- If numerous people access the web GIS system simultaneously, the speed of processing and computation slows dramatically.
- This NAPRA Web GIS system does not reside on one dedicated server, so operation of the system can be affected by other processes on the server.
- Sometimes, users may want to run the model with their own data such as a site-specific soil map, but this system does not allow users to upload such maps to the NAPRA Web GIS server.

To solve these problems, efforts are underway to create a code to process NAPRA runs and generate maps one by one since it usually takes less than several seconds to process GIS data. The web GIS version of the NAPRA system will be extended nation-wide and a dedicated server for the web GIS version of the NAPRA will be used. Also, capabilities to allow uploading site-specific soil data to the NAPRA Web GIS server are being developed to improve model estimation.

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